Ultra-high resolution in the scanning electron microscope (SEM)

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Purpose

• **Discuss the limitations on resolution limit in the scanning electron microscope**

• **Describe methods for overcoming resolution limits in the scanning electron microscope**

Outline

- Electron optics
- Electron beam / sample interaction
- STEM-in-SEM approach
- Forward scattered imaging approach
- Image processing
- He ion microscopy

Background

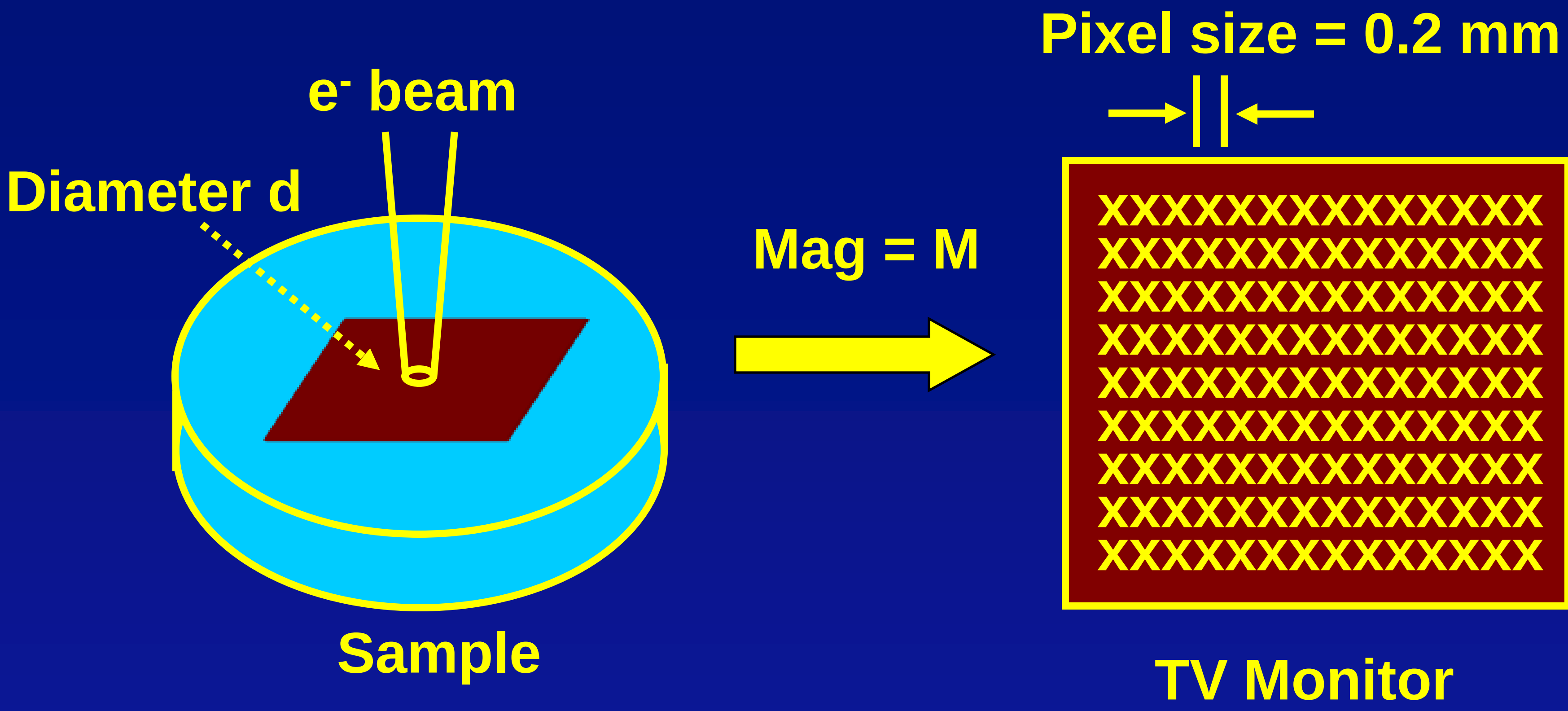
• The SEM is an incredibly versatile tool for high resolution imaging due to simply sample preparation, ease of use, and high depth of field.

• Device features below 0.1 micron size are pushing the resolution limit of SEM.

• TEMs and AFMs are now replacing SEMs for fine line metrology.

• Modern SEM have 1 nm spot size, but 1 nm SEM resolution is seldom seen on “real” samples.

Maximum useful magnification



Beam diameter d when translated to the monitor has diameter d*M

Maximum useful magnification

Image in sharp focus

$d * M \leq 0.2$ mm

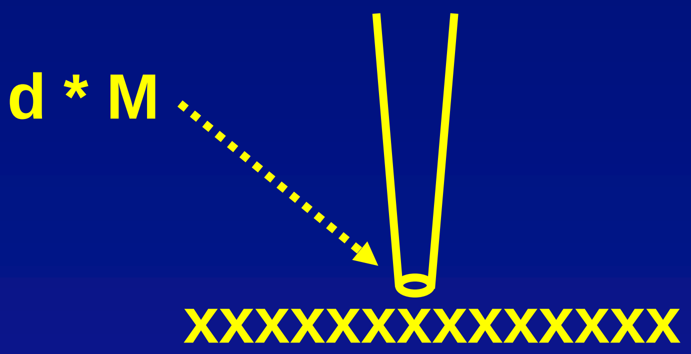
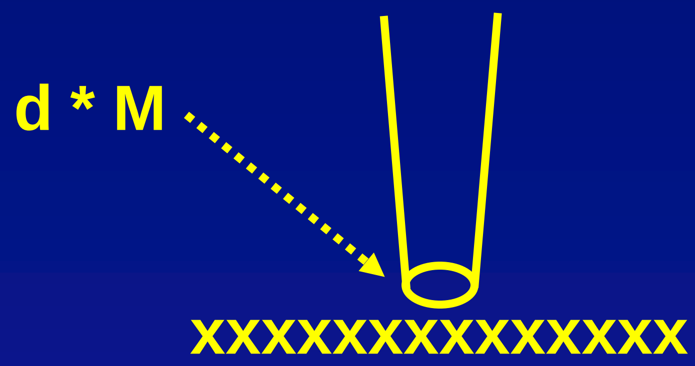


Image not in sharp focus

$d * M > 0.2$ mm



$$M_{max} = 0.2 \text{ mm} / d$$

For d = 5 nm, the maximum useful mag is 40,000x

For d = 1 nm, the maximum useful mag is 200,000x !!!

Factors affection SEM resolution

- Electron beam spot size
- Contrast and signal intensity
- Beam/sample interaction

Brightness

$$\text{Brightness} = \beta = \frac{\text{current}}{\text{area x solid angle}} = \frac{4\,i}{\pi^2\ d^2\ \alpha^2}$$

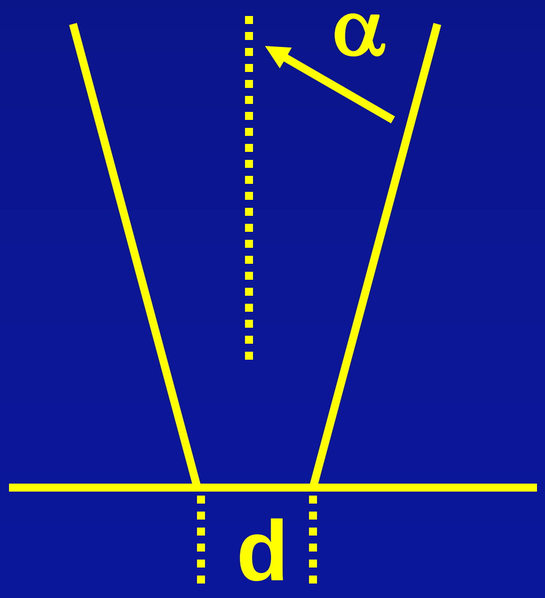
β = brightness

i = beam current

d = beam diameter

α = convergence angle

π = Pi ~ 3.14



Maximum Brightness

$$\beta_{max} = \frac{J_c \, e \, V_o}{\pi \, k_b \, T}$$

β_{max} = maximum brightness

Jc = current density at cathode (Amps/cm^2)

e = electron charge = 1.6 x 10^{-19} Coulomb

V_o = beam accelerating voltage (volts)

k_b = Boltzman's constant (8.6x10^{-5} eV/K)

T = Cathode temperature (K)

π = Pi ~ 3.14

SEM Cathode Comparison

Source:	Tungsten	LaB_6	Schottky Field Emission	Cold Field Emission
Vacuum: (torr)	10^{-5}	10^{-7}	10^{-8}	10^{-10}
Brightness: ($A/cm^2 \cdot sr$)	10^{+5}	10^{+6}	10^{+8}	10^{+8}
Resolution:	10 nm	5 nm	1 nm	1 nm
Lifetime (hours)	40-100	200-1000	>1000	>1000

Gaussian spot size

$$d_g = \left[\frac{4\,i}{\beta\ \pi^2\ \alpha^2} \right]^{1/2}$$

d_g = Gaussian spot size, i.e. final spot size in the absence of lens aberrations

Final probe size

$$d_p = \left[d_g^2 + d_s^2 + d_d^2 + d_c^2 \right]^{1/2}$$

d_p = final probe size

d_s = spherical aberration = $C_s\ \alpha^3 /2$

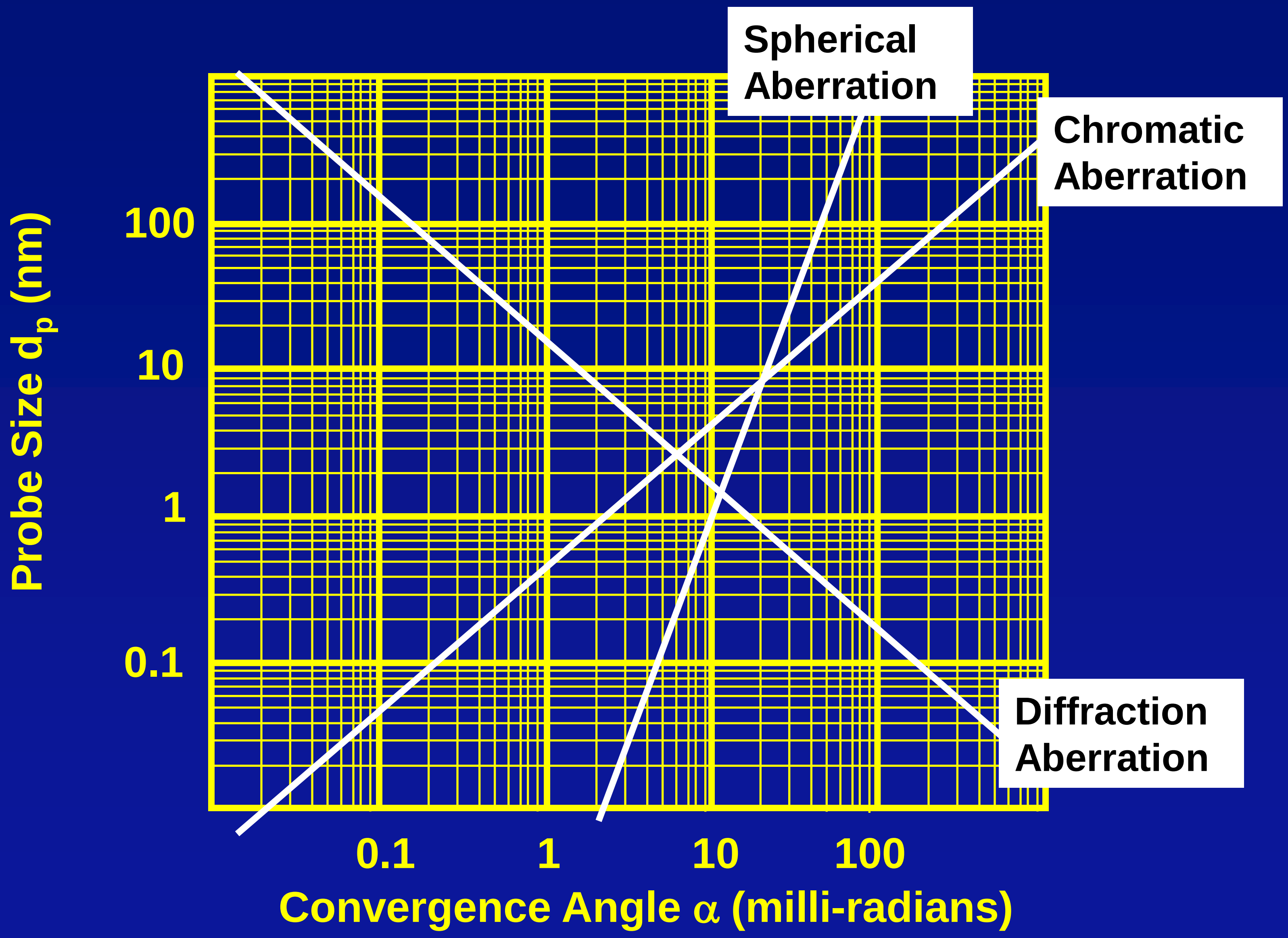
d_d = diffraction aberration = $0.61\ \lambda\ /\ \alpha$

d_c = chromatic aberration = $C_c\ \alpha\ \Delta E/E_o$

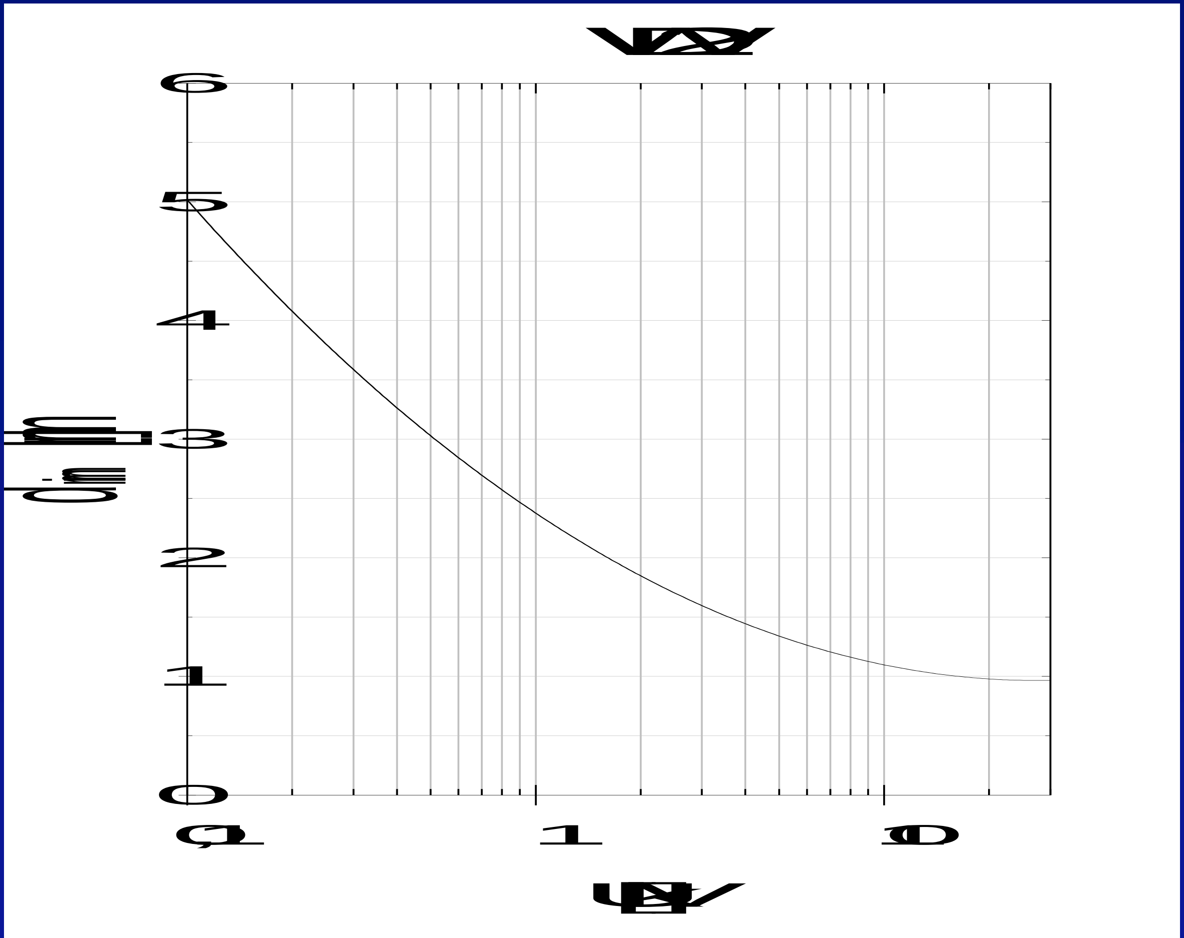
Where: C_s ~ 2cm C_c ~ 2 cm

λ = electron wavelength ~ 0.2 to 1.2 nm

Probe size vs. convergence angle for electron optical aberrations



LEO 1550 FE “Gemini” Column Specs

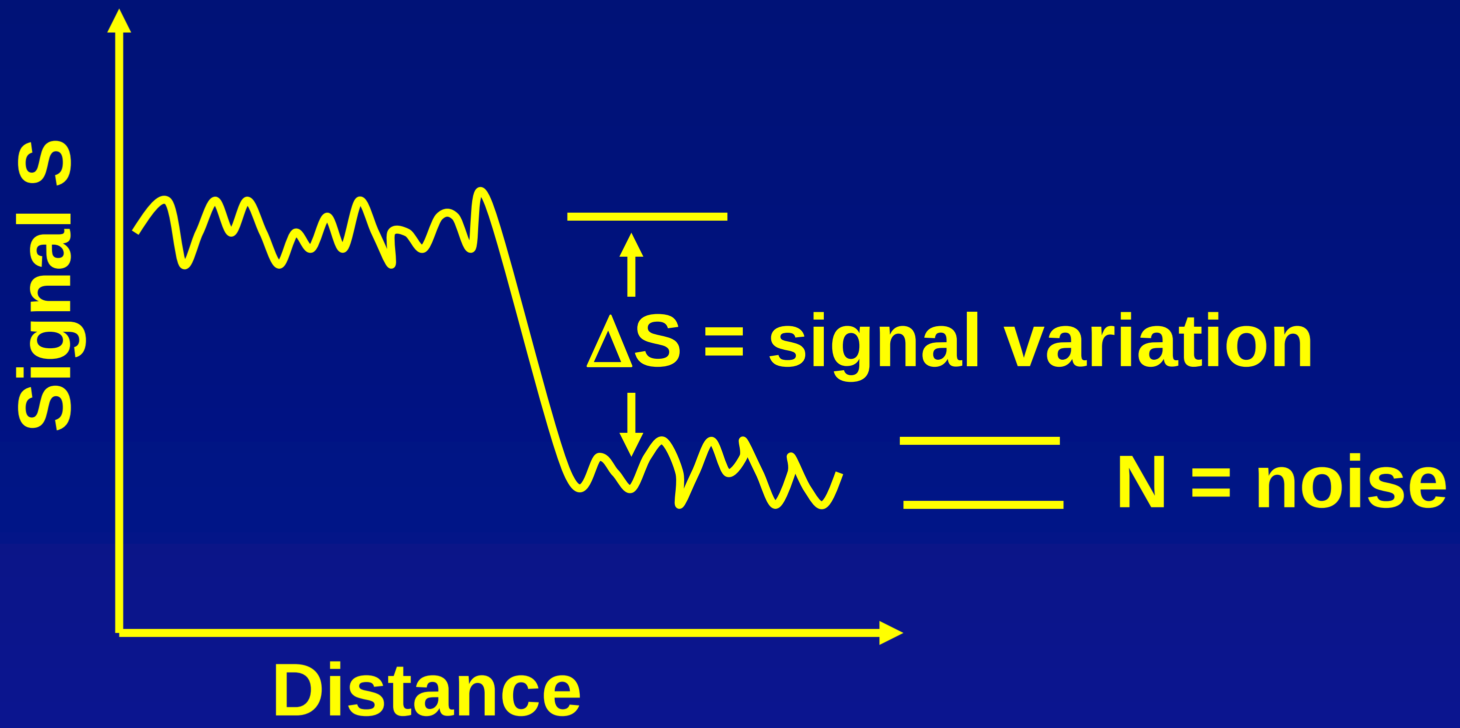


d = 1.0 nm @ 20 kV

d = 2.3 nm @ 1 kV

Resolution vs. beam voltage for LEO 1550 FE

Visibility and the Rose Criterion



Rose Criterion: for a feature to be visible, $\Delta S > 5N$

Random noise $N \sim \bar{n}^{1/2}$ where $\bar{n}$ = mean number of counts

Contrast $C = \Delta S/S$

Then the Rose criterion requires $\bar{n} > (5/C)^2$

Threshold Equation

$i_B > (4 \times 10^{-12} / \varepsilon C^2 t_f)$ Amps

Where:

i_B = beam current

ε = collection efficiency (# electrons collected per incident electron)

C = contrast

t_f = frame time (for 1,000 x 1,000 frame with 10^6 pixels)

1 Amp = 6.24×10^{18} electrons/sec

Typical high-resolution imaging slow scan:

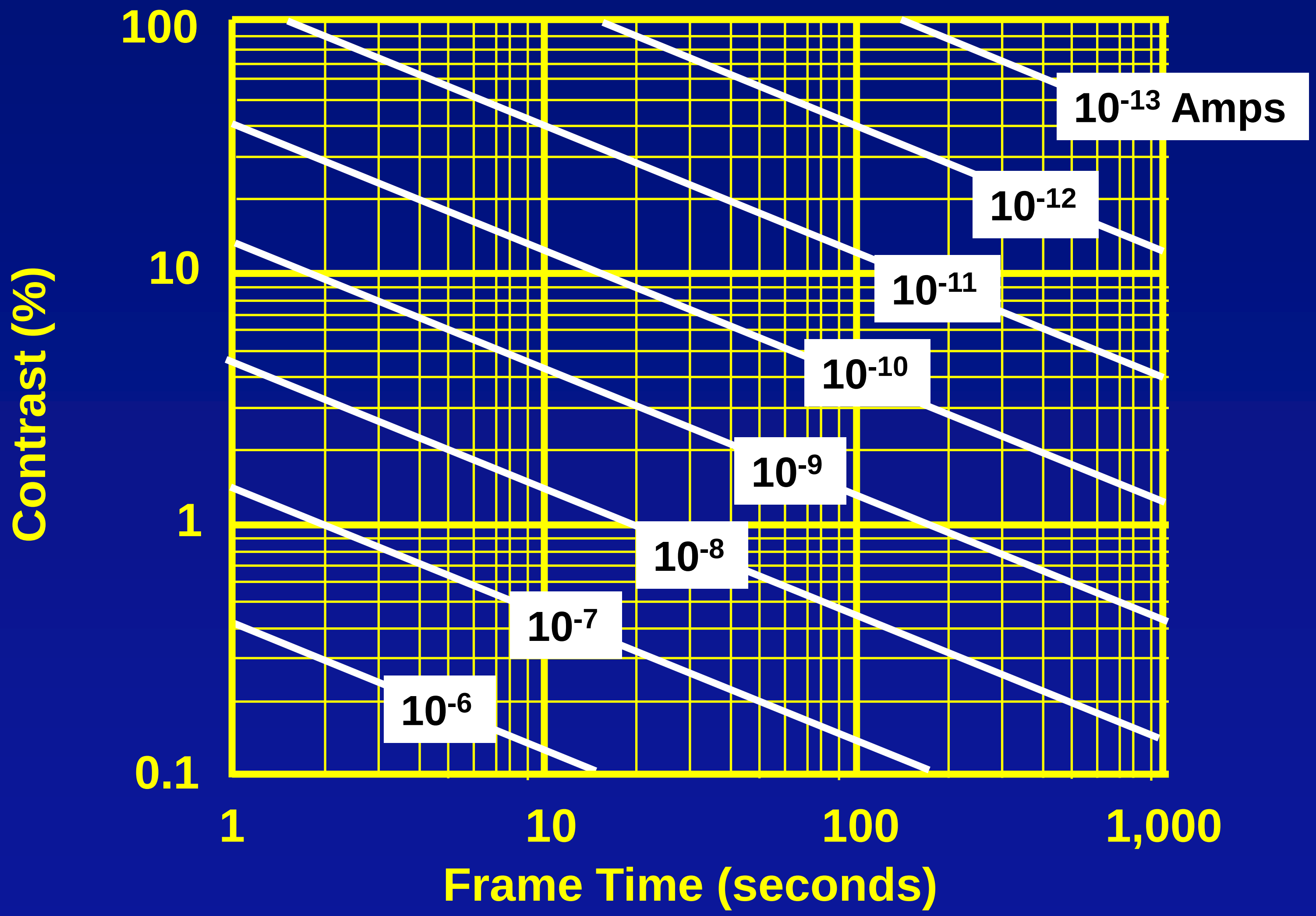
i_B = 30 pA = 1.9×10^8 electrons/sec

$\varepsilon = 0.25$

t_f = 30 seconds

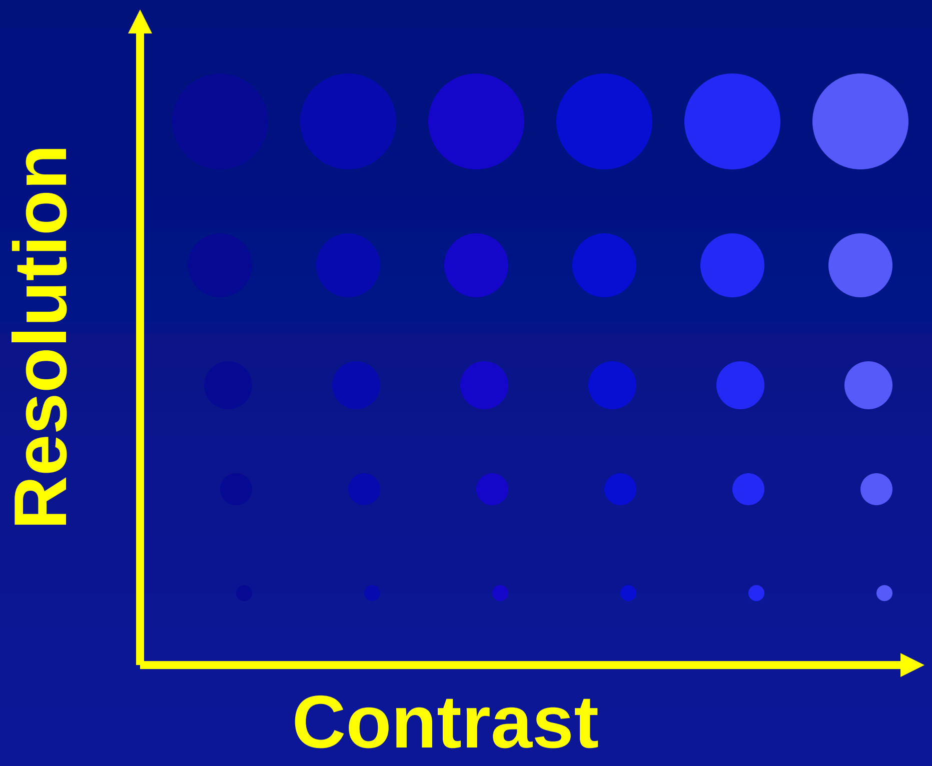
Then: $C \geq 0.13$

Threshold Equation

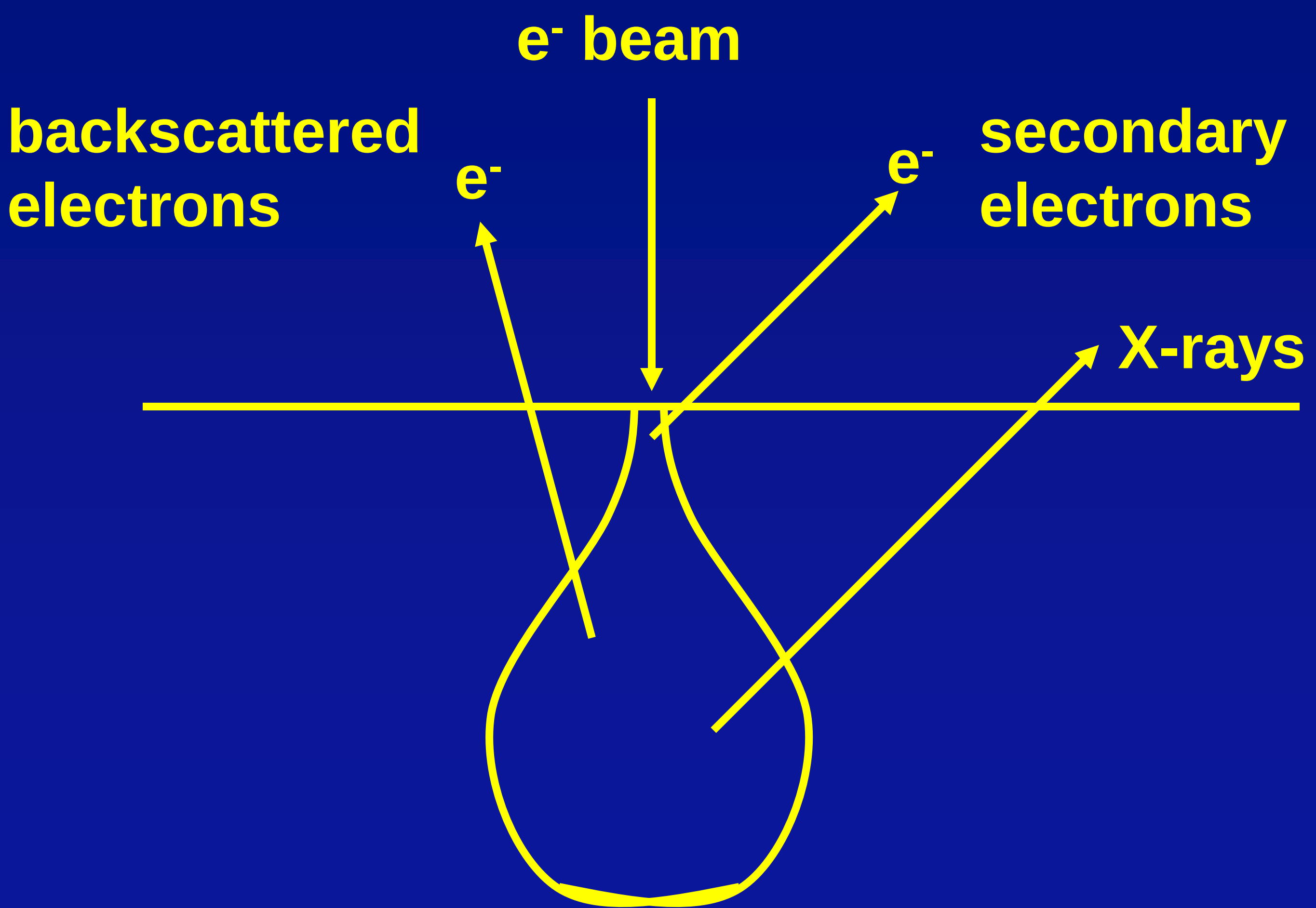


After Goldstein Fig. 4.41

Visibility vs. resolution and contrast



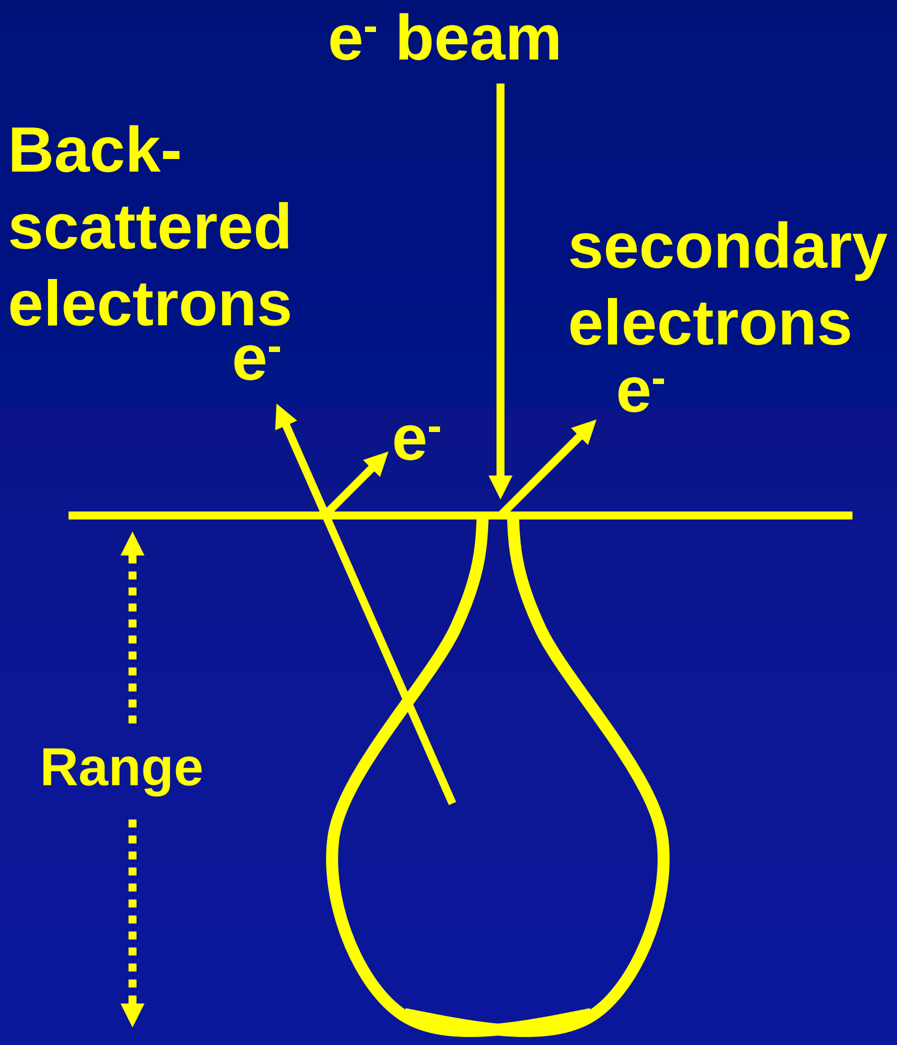
Electron Beam-Sample Interaction Products



Electron beam energy vs. range & spot size

Beam energy (keV)	Spot size (nm)	Range in Al (μm)
1	2.4	0.028
3.5	1.5	0.22
5	1.3	0.41
10	1.1	1.32
20	1.0	4.19
30	1.0	8.24

Range calculated from the Kanaya-Okayama formula



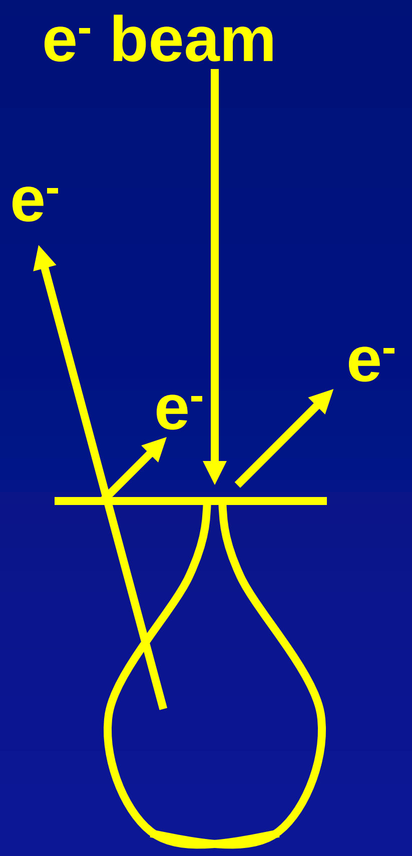
Ultra-high Resolution SEM

Requirements for ultra-high resolution SEM:

(1) An electron beam finely focused to a <u>small spot</u> at the sample surface.

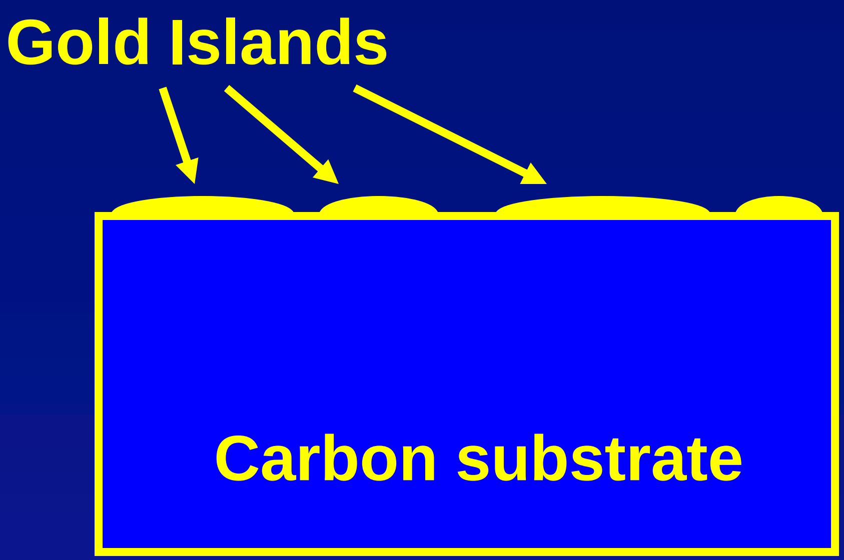
(2) Sufficient electron beam <u>current</u> to produce good image <u>contrast</u>.

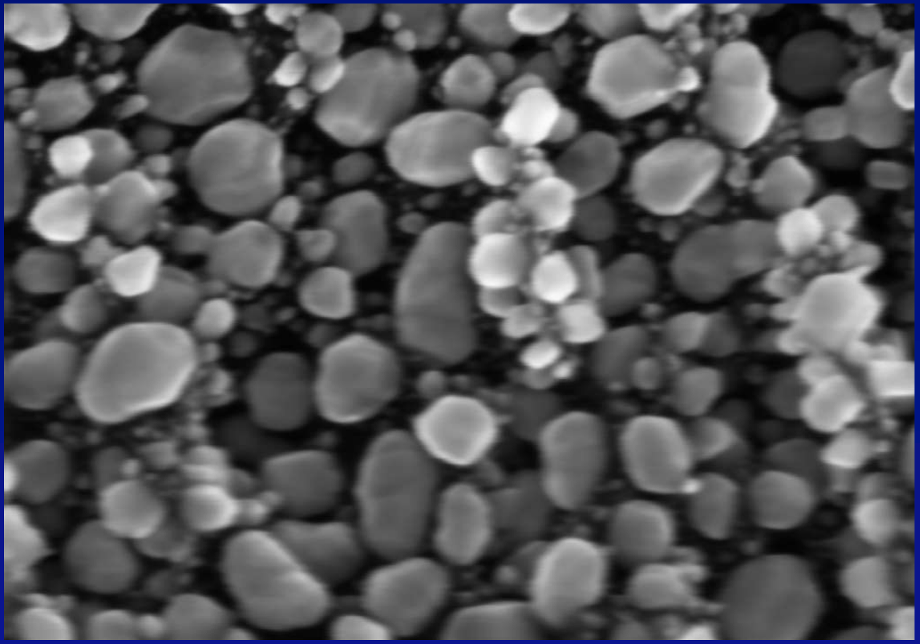
(3) An imaging signal which is well <u>localized</u> to the electron beam impact site.



(1) and (2) generally require high electron beam voltage, which causes problems obtaining (3).

Gold-on-Carbon Resolution Sample

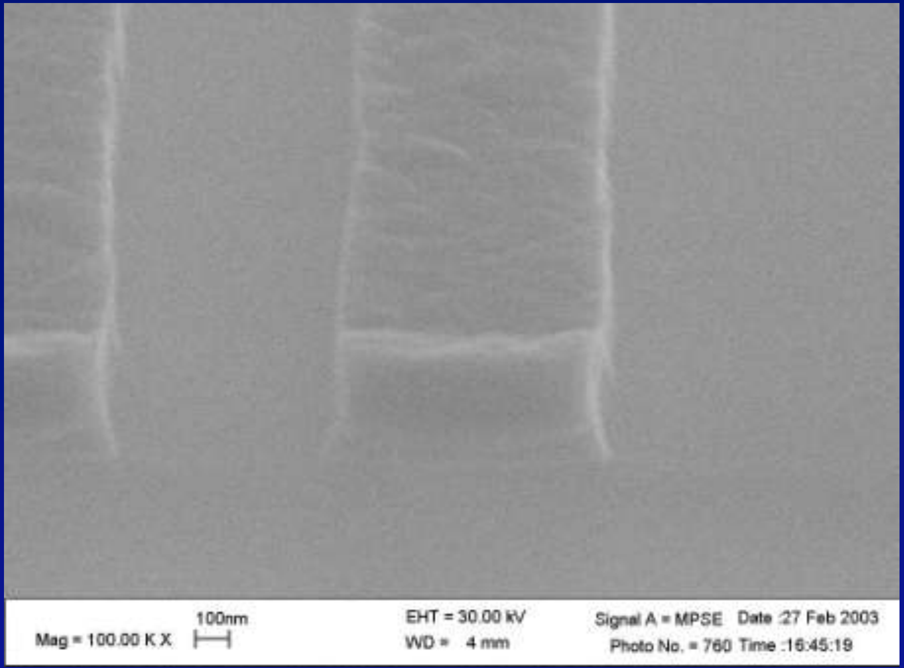




100 nm
Mag = 500,000 x

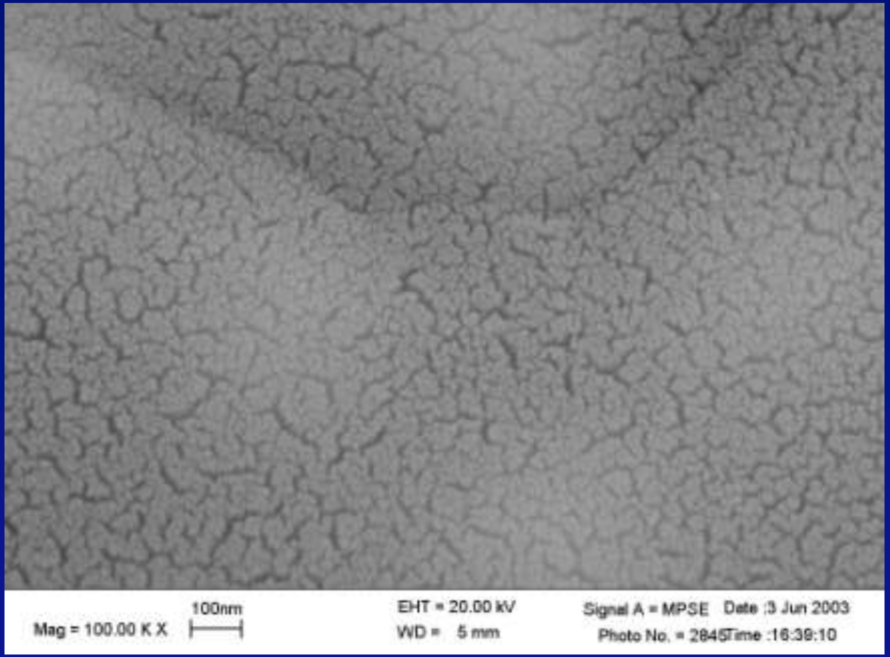
A highly reflective pattern (gold islands) on a strongly absorbing substrate (carbon) allows very high resolution imaging at high beam voltage.

Typical Samples at high kV



0.1 µm – Mag = 100,000 x

Uncoated sample –
Poor image



0.1 µm – Mag = 100,000 x

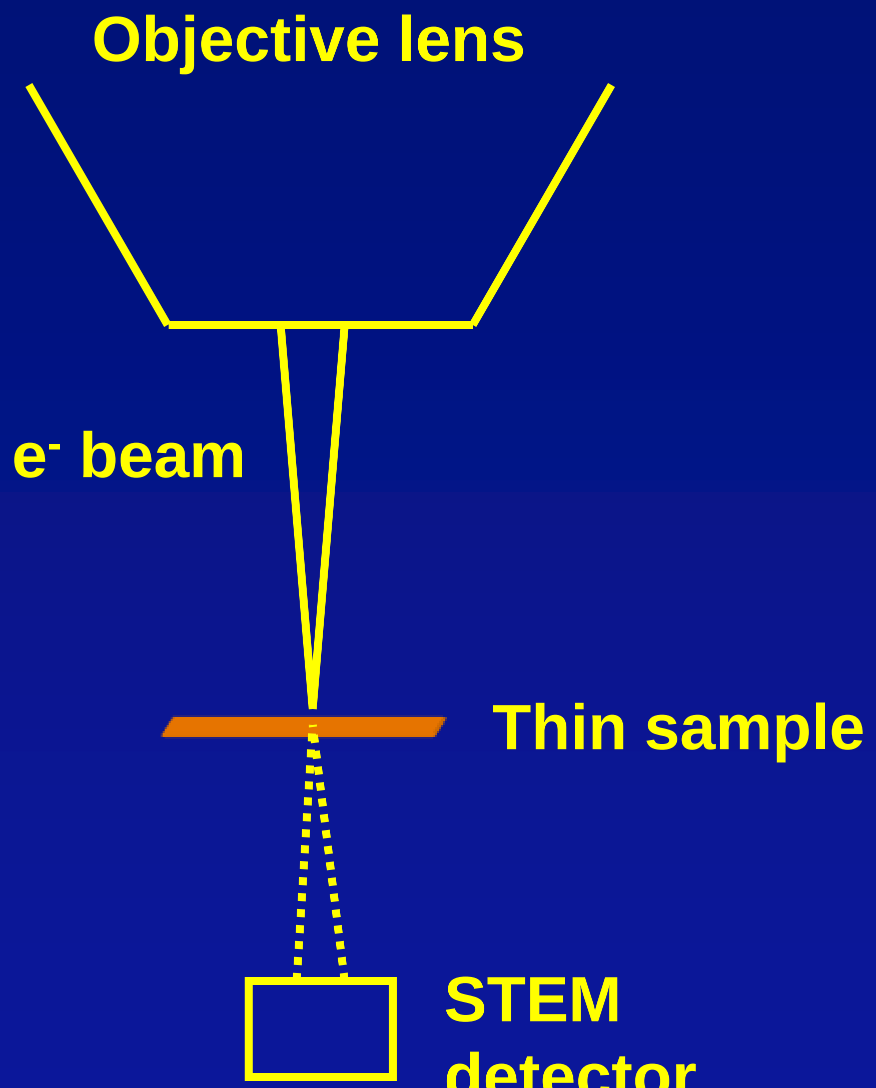
Coated sample –
Coating artifacts

Ultra-High resolution SEM

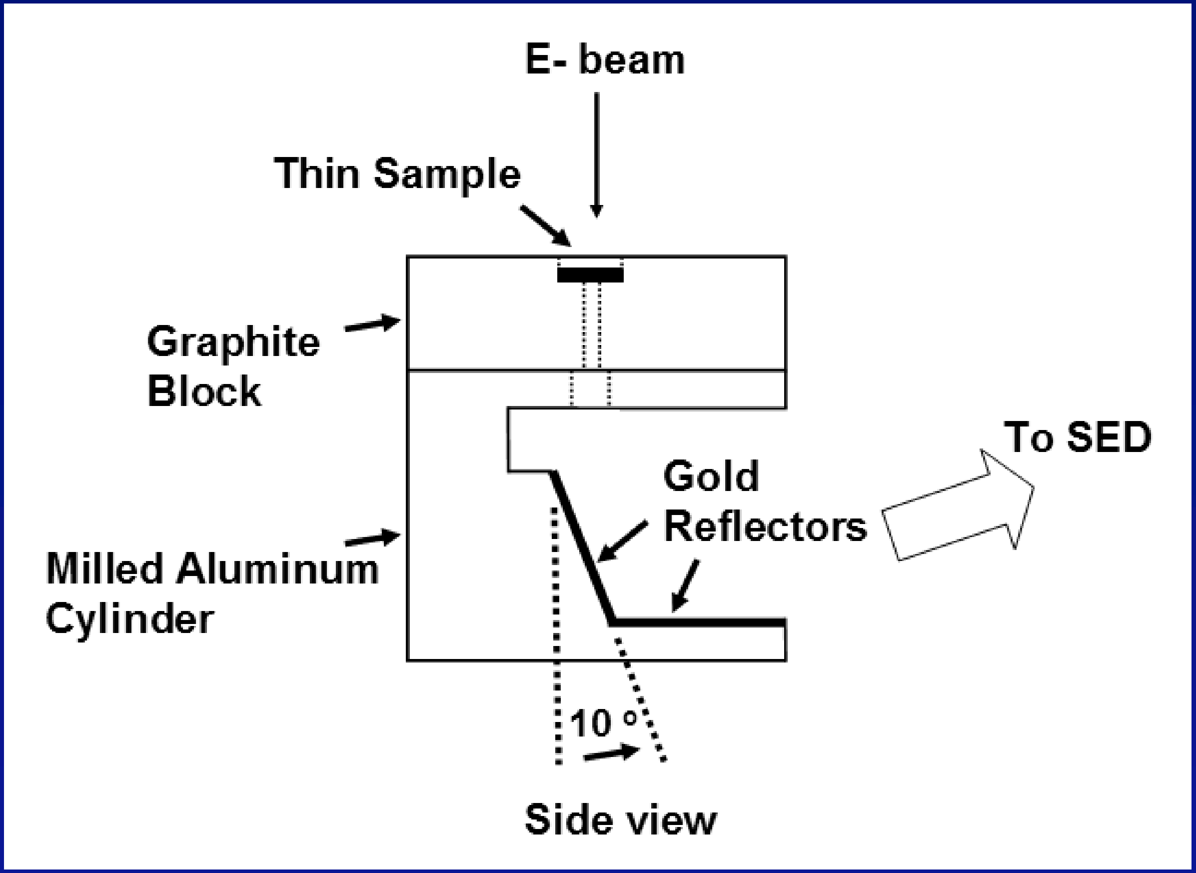
Part 1:

STEM-in-SEM

STEM-in-SEM

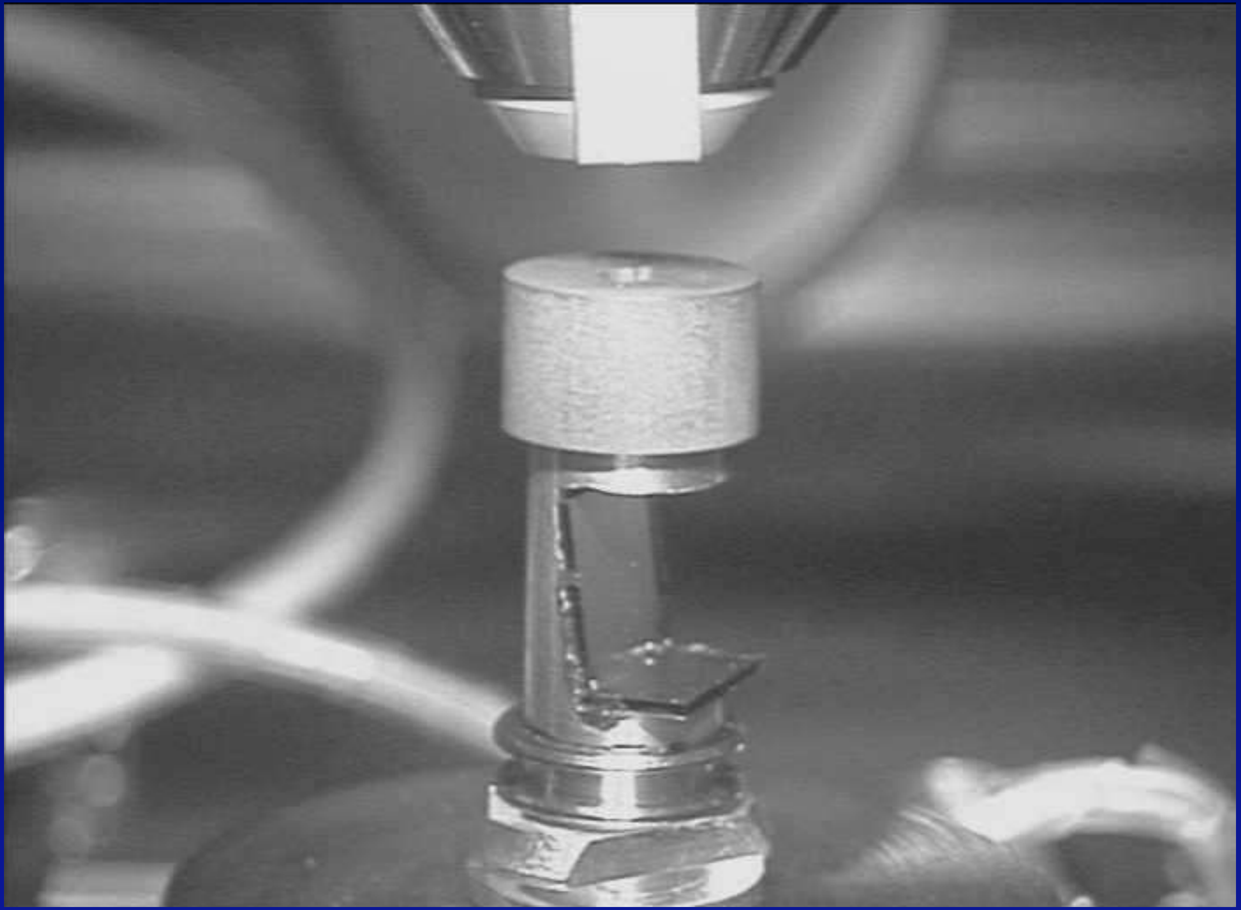


STEM-in-SEM



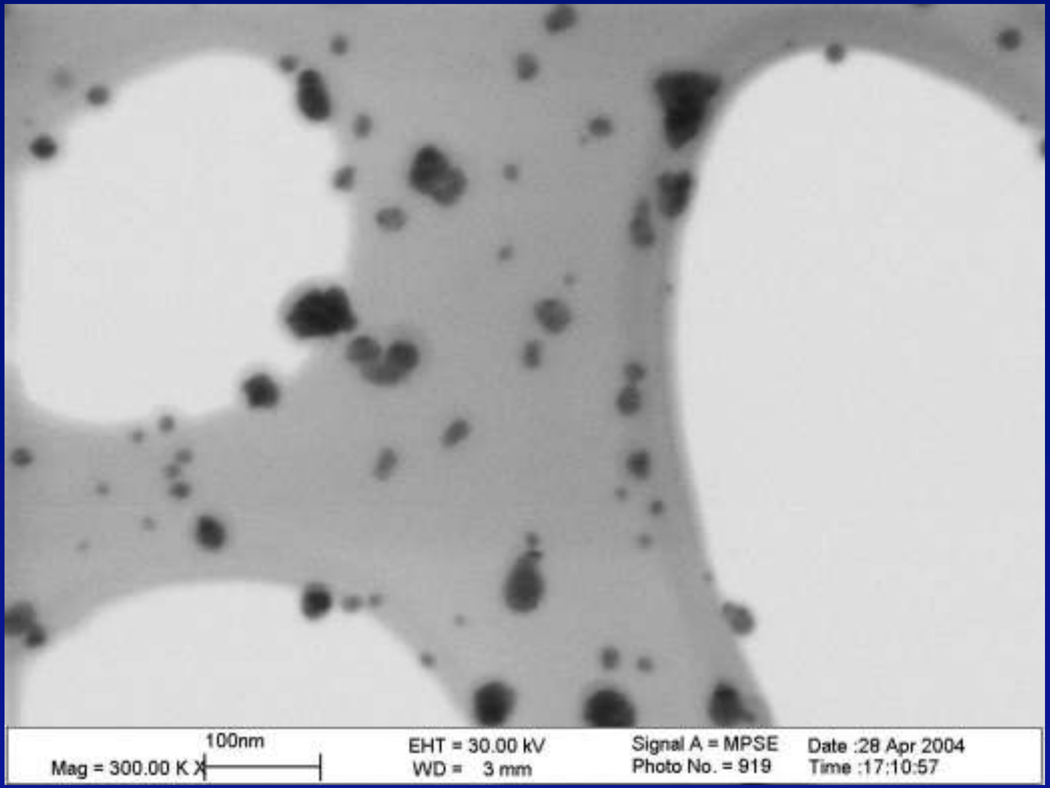
Electrons pass through the thin sample and strike the gold reflectors, creating secondary electrons which are collected by the in-chamber secondary electron detector (SED).
[per David Joy]

Sample holder in operation

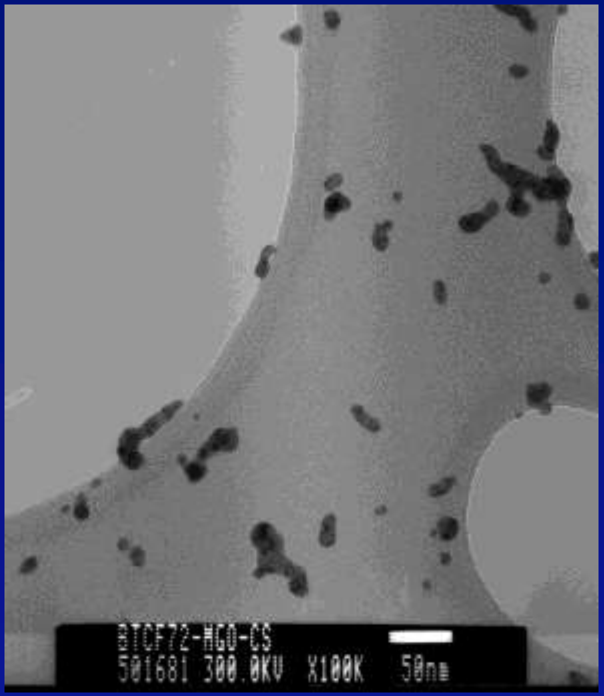


The STEM-in-SEM sample holder is placed in the SEM just like any other sample.

STEM-in-SEM vs. TEM



SEM: 30 kV

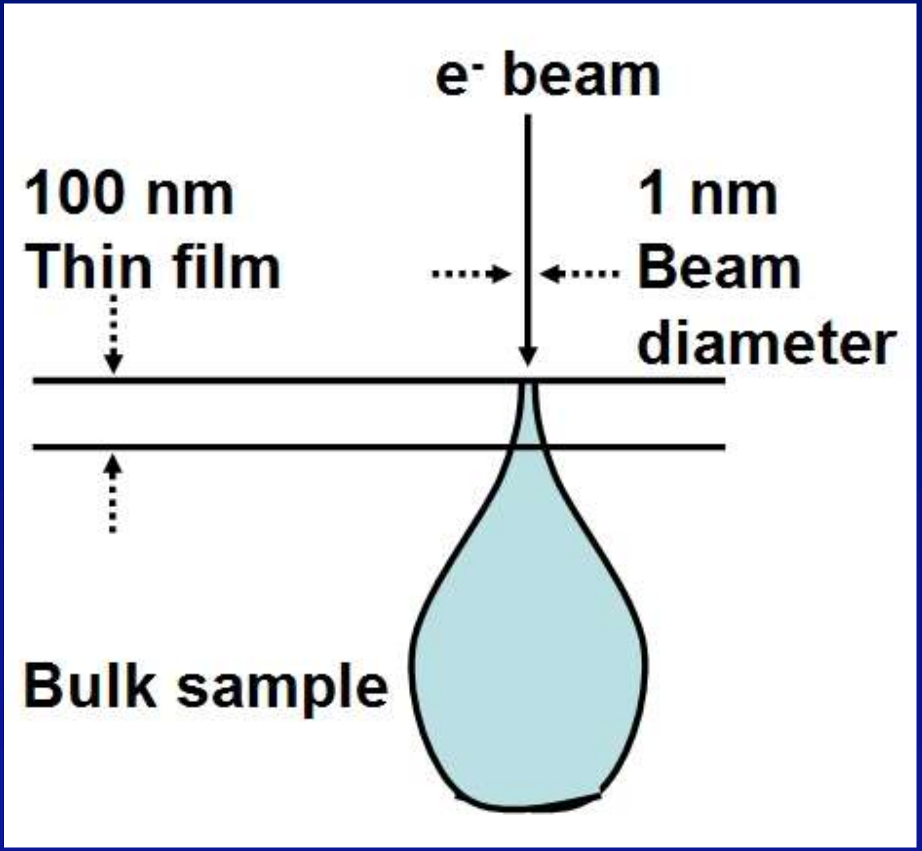


TEM: 300 kV

Silver nanoparticles (aerosol process) on "holey carbon film"

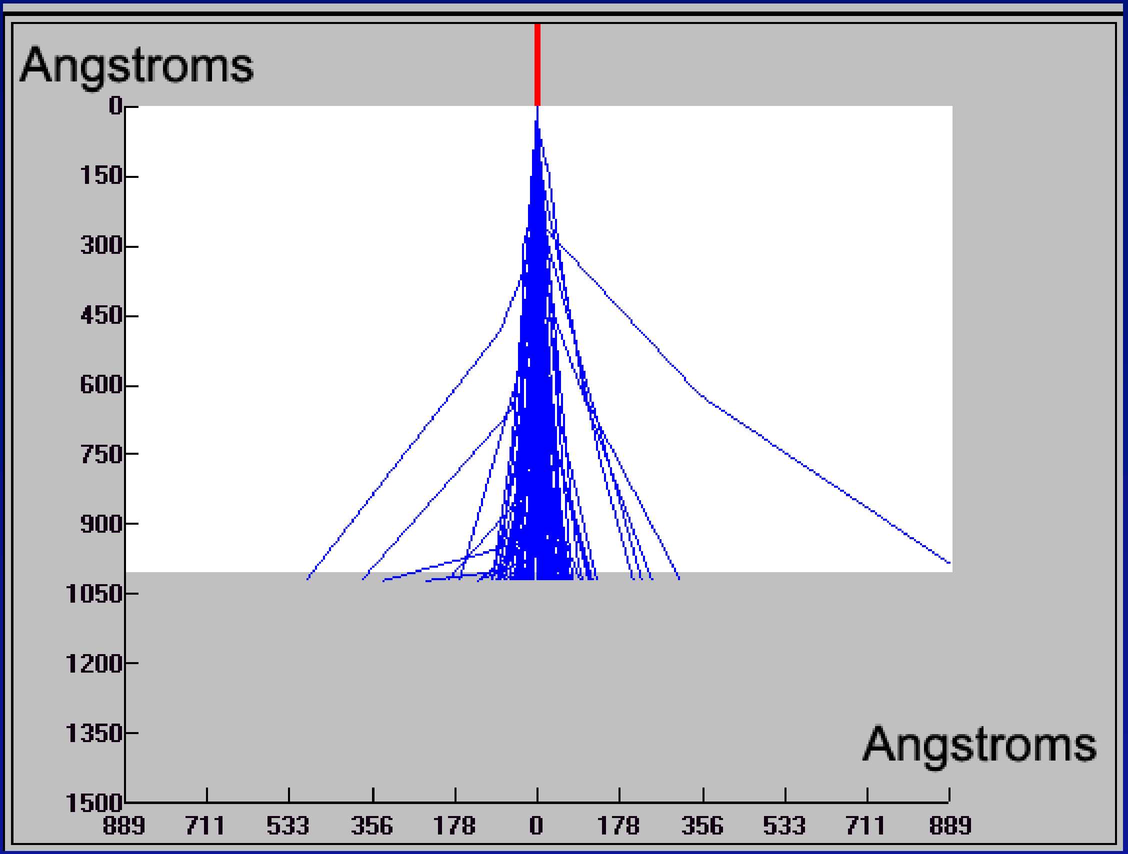
Electron beam Penetration in Silicon

Electron beam energy (keV)	Electron penetration depth in silicon (microns)
5	0.47
10	1.49
15	2.93
20	4.73
25	6.87
30	9.31



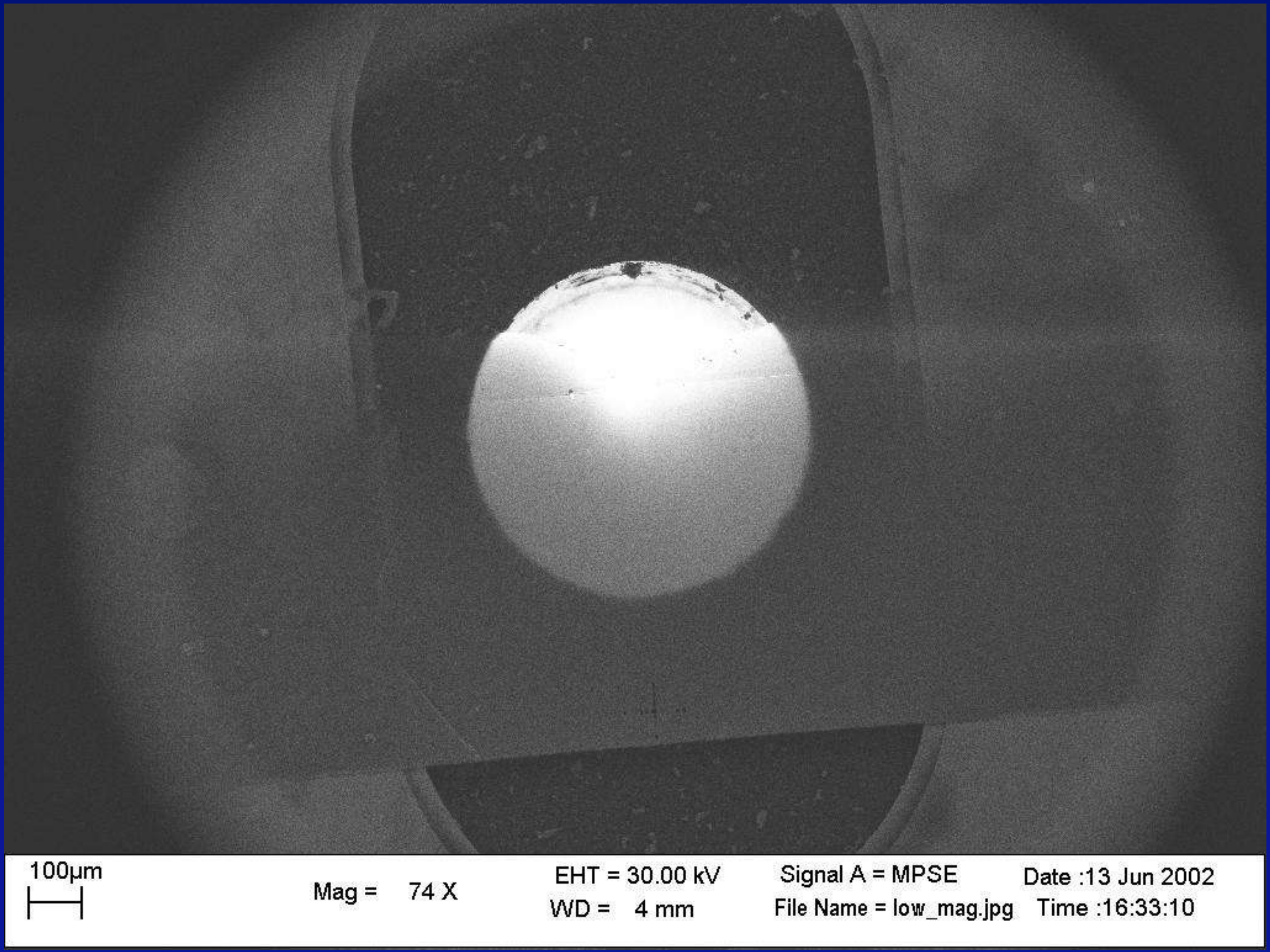
At 100 keV the scattering length is much greater than 100 nm, but at 30 keV the scattering length is 17 nm.

Monte-Carlo simulation of electron trajectories at 30 keV



Lateral scattering increases the electron beam spot size from 10 Angstroms to 350 Angstroms, reducing resolution.
The graphite collimator blocks the most highly scattered electrons, which improves resolution.

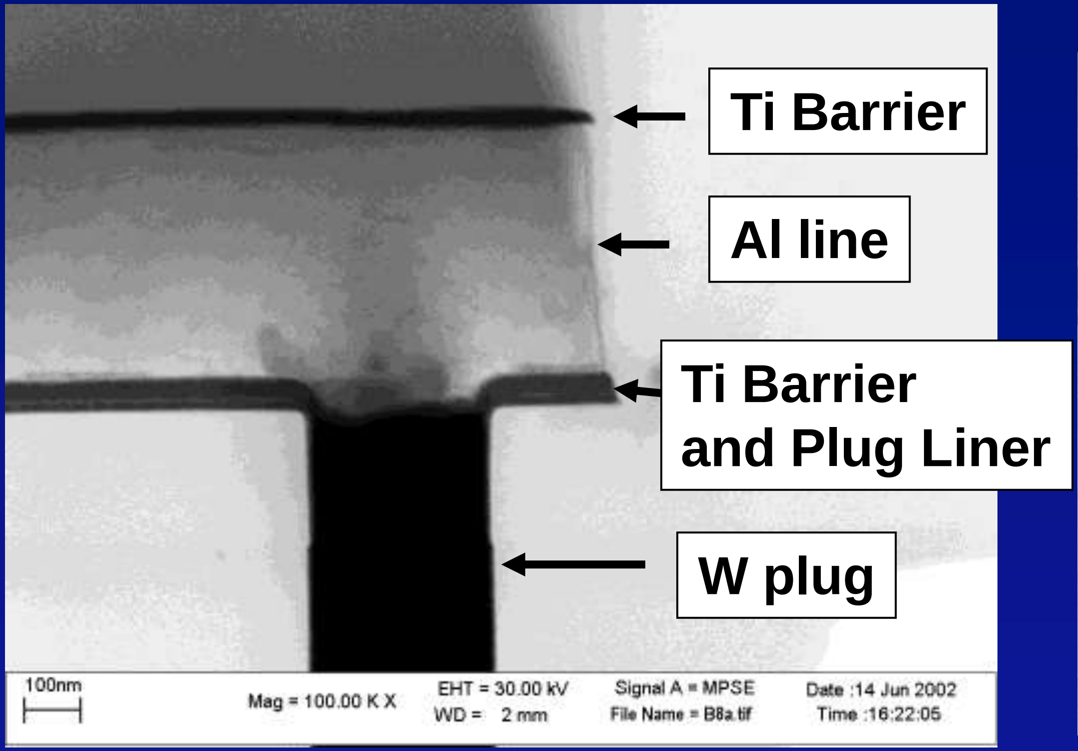
Low magnification STEM-in-SEM image



— 100 µm   Mag = 75x

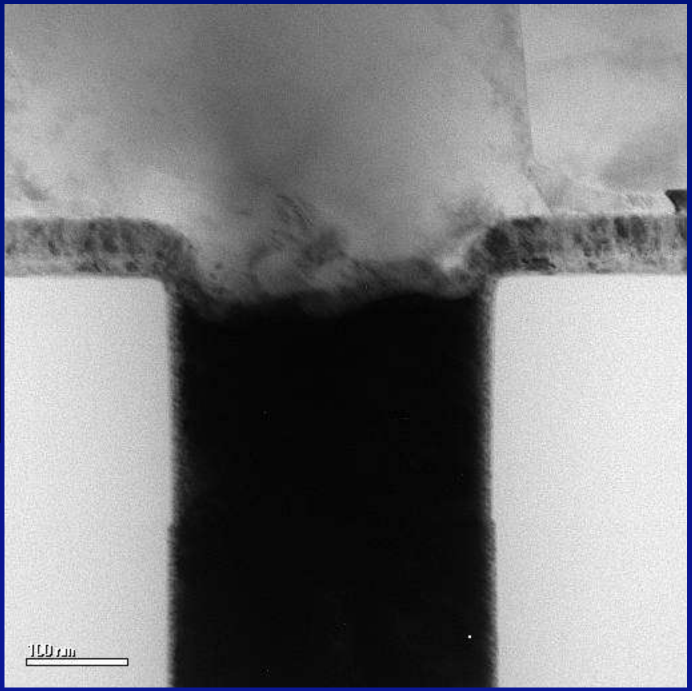
STEM-in-SEM vs. TEM images

STEM-in-SEM



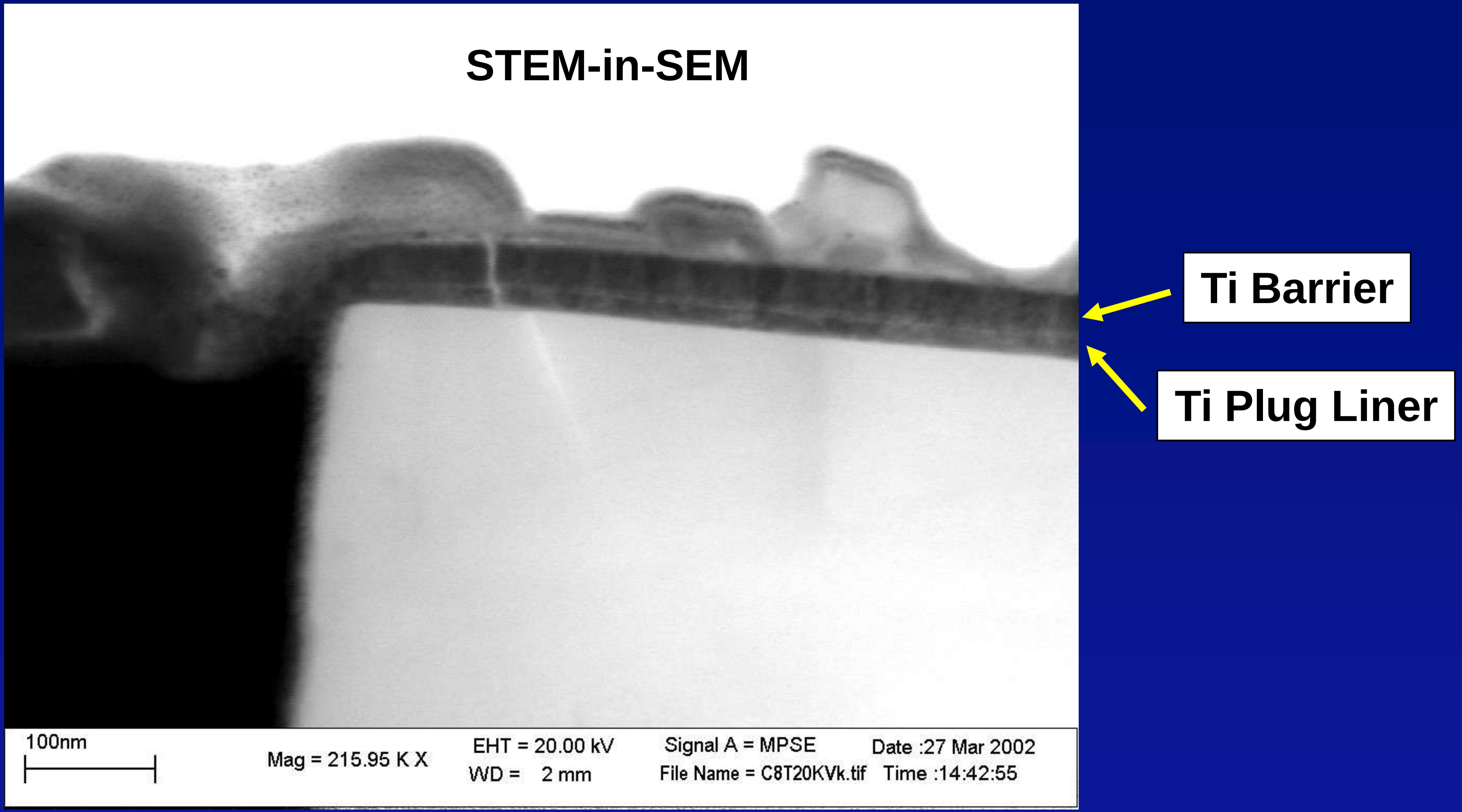
— 100 nm Mag = 100,000x

TEM



— 100 nm Mag = 240,000x

High magnification STEM-in-SEM

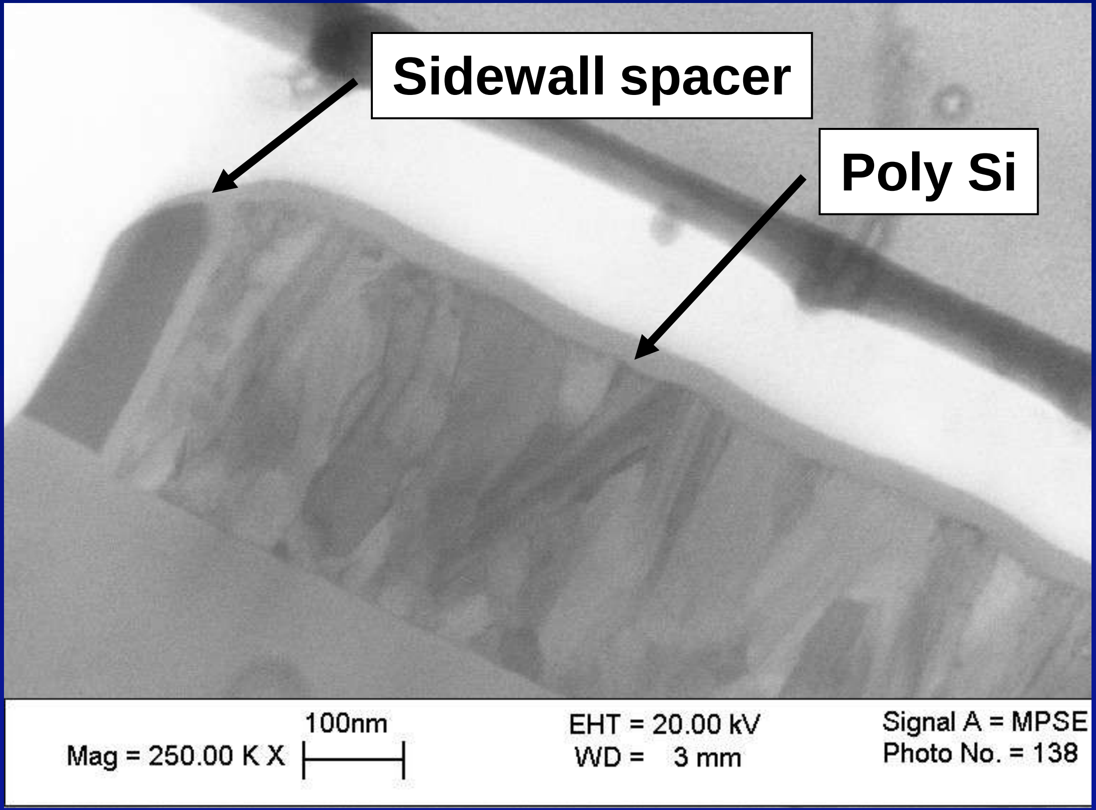


100 nm

Mag = 216,000x

STEM-in-SEM vs. TEM images

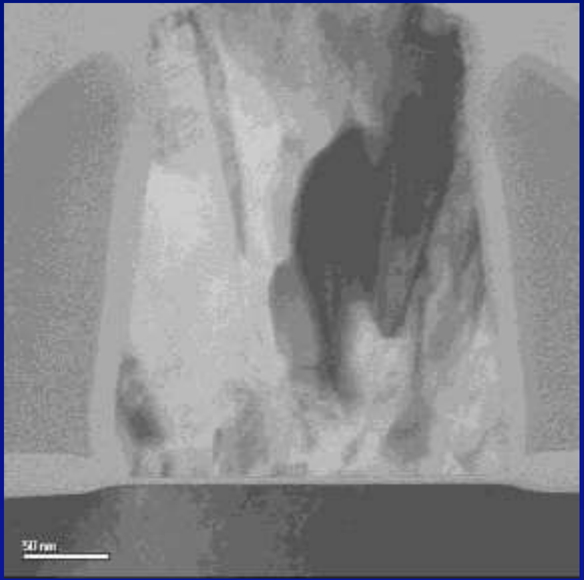
STEM-in-SEM



— 100 nm Mag = 250,000x

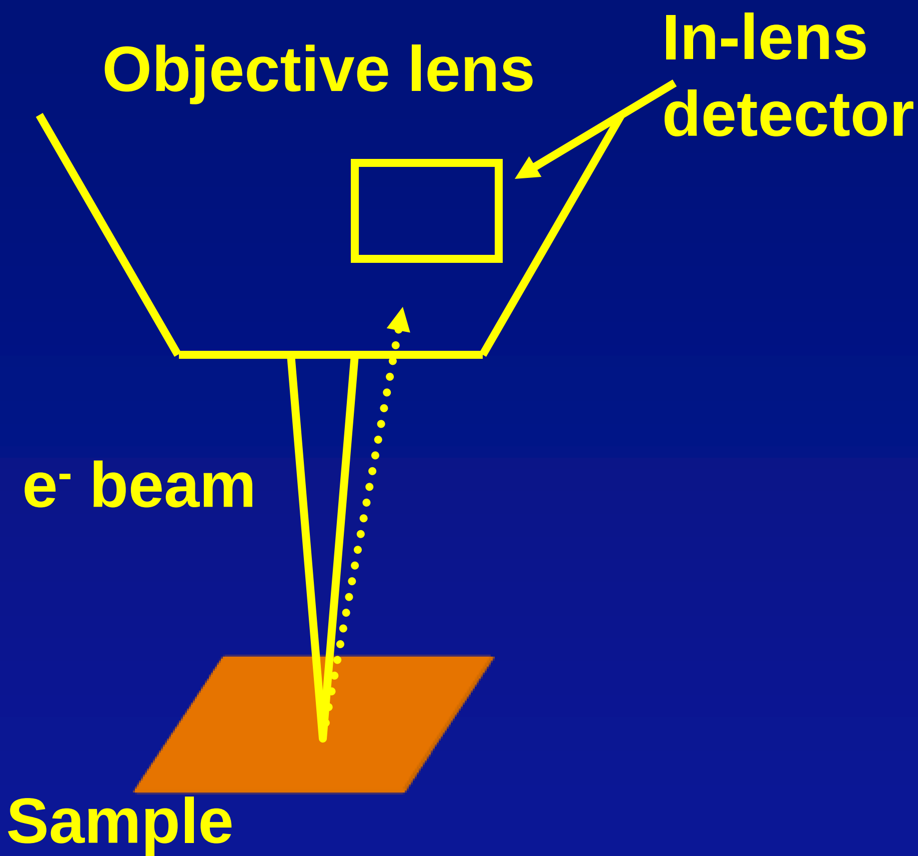
Resolution ~ 2 nm

TEM

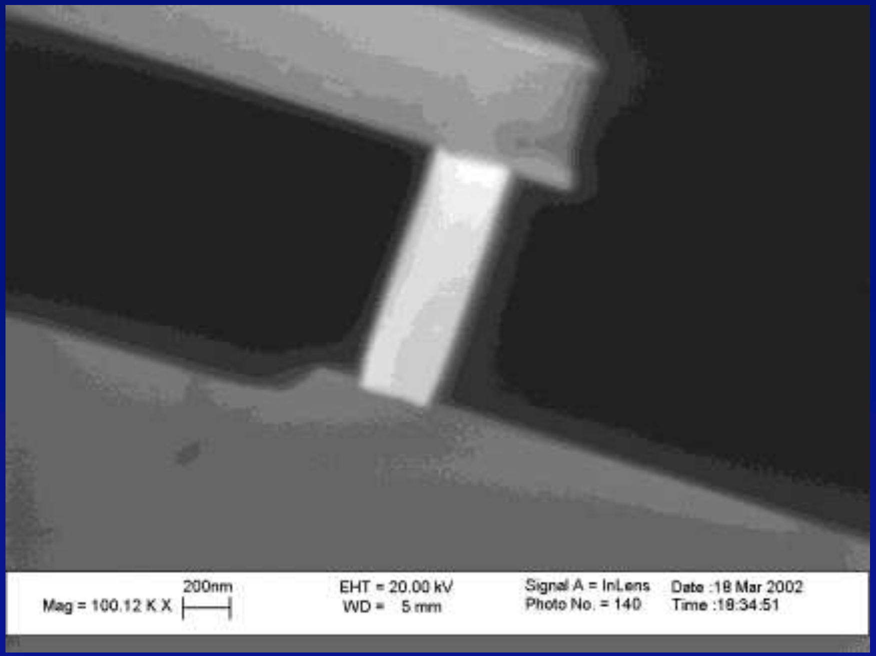


— 50 nm Mag = 500,000x

In-lens secondary image



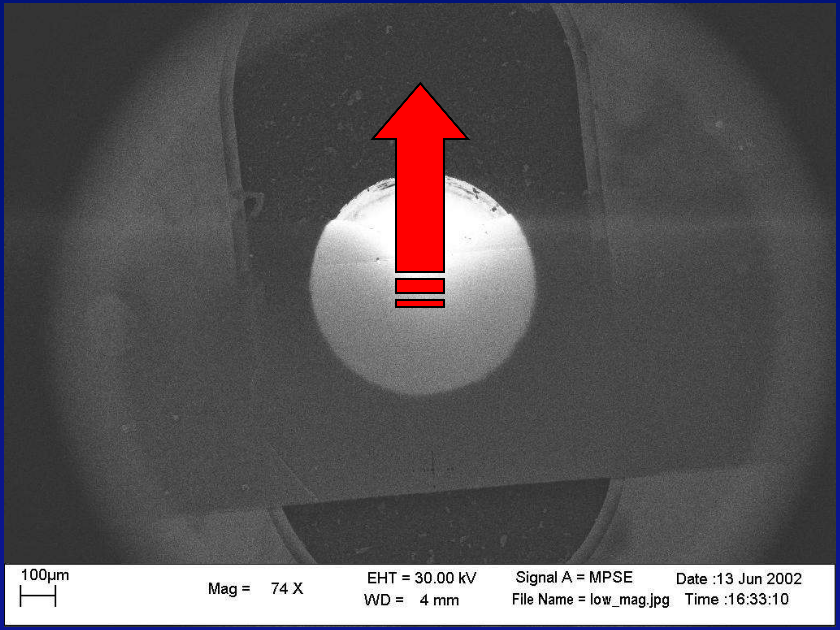
SEM on thin sample



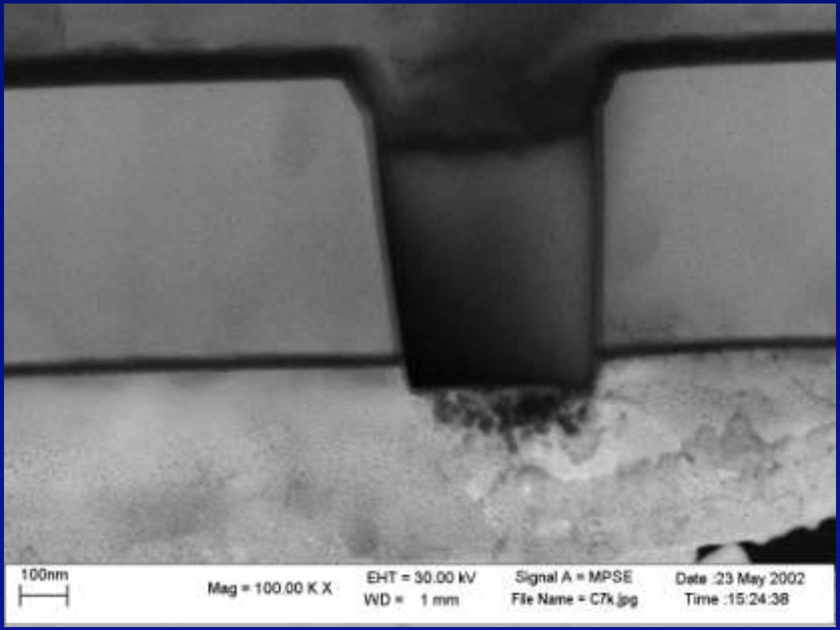
— 200 nm Mag = 100,000x

Using an “in-lens” detector, the image is little better than using ordinary SEM.

Dark field STEM-in-SEM imaging



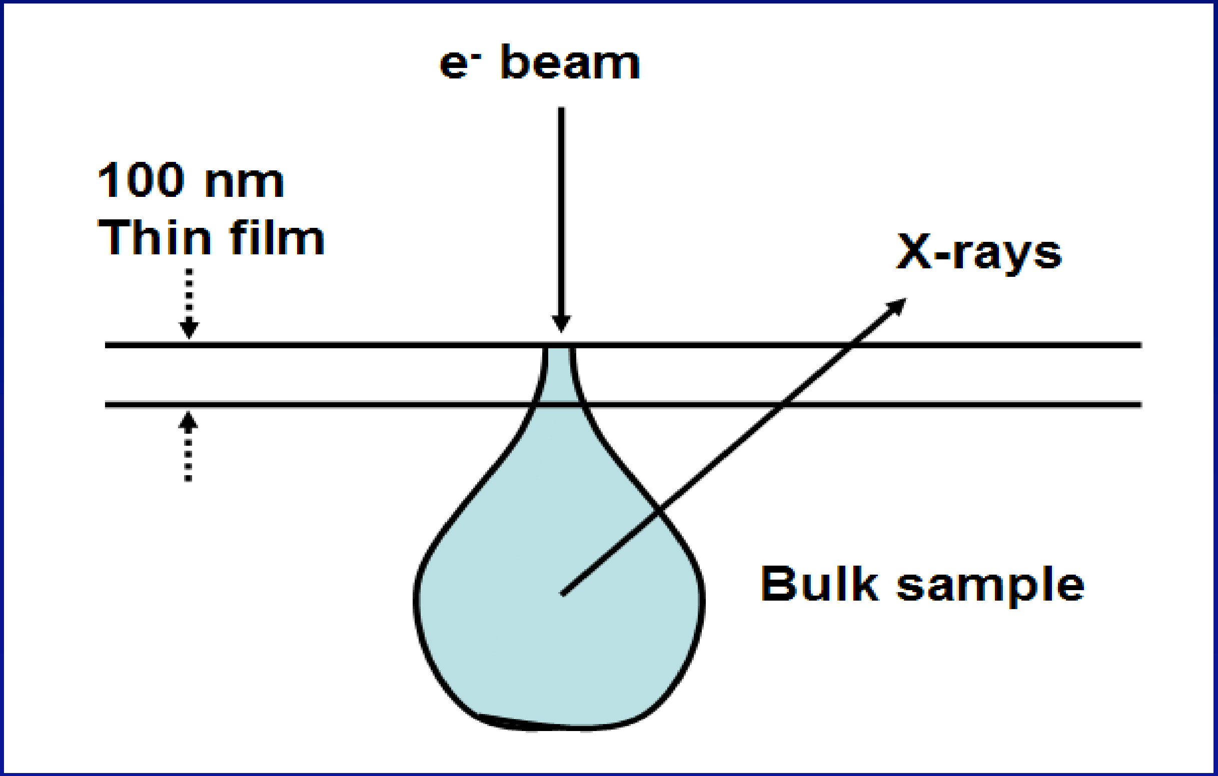
– 100 µm Mag = 75x



— 100 nm Mag = 100,000x

When the area of interest is moved away from the collimator, only the most highly-scattered electrons are collected. This "dark-field image" emphasizes scattering contrast.

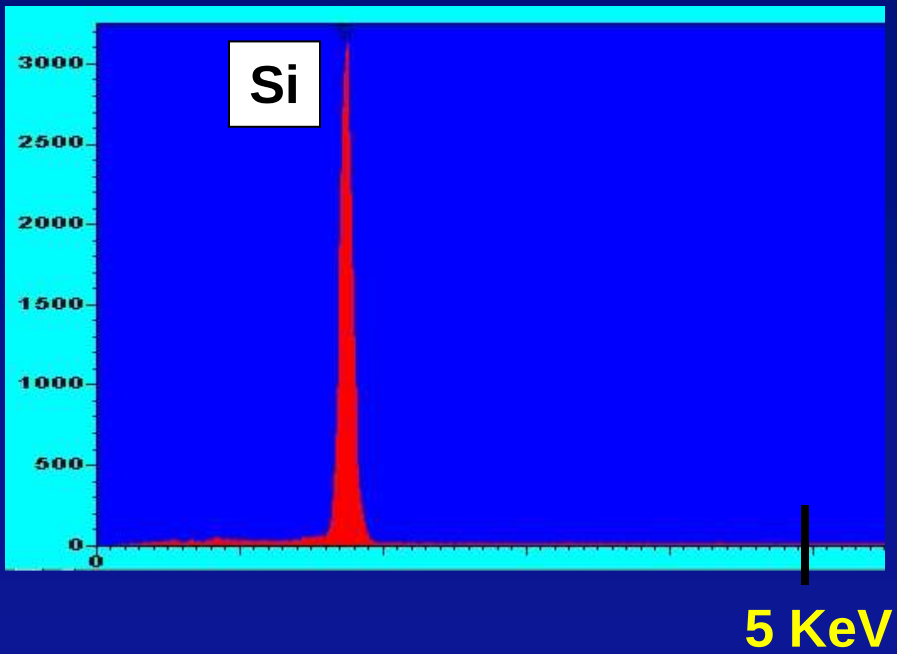
Energy dispersive x-rays from bulk and thin films



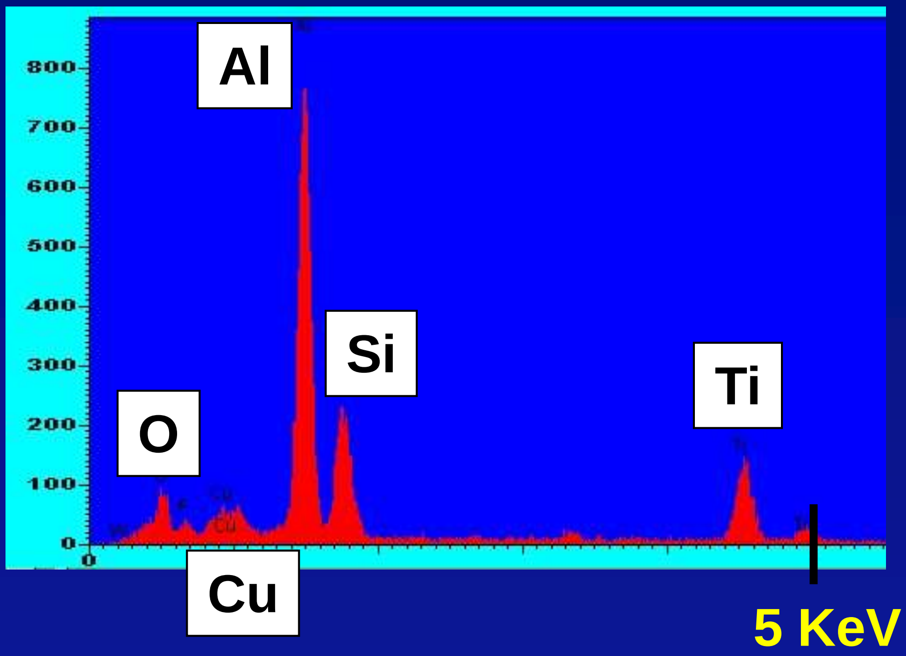
Using a thin film sample greatly reduces the lateral area in which x-rays are generated.

EDS Spectra of thin films

EDS spectrum of thin silicon

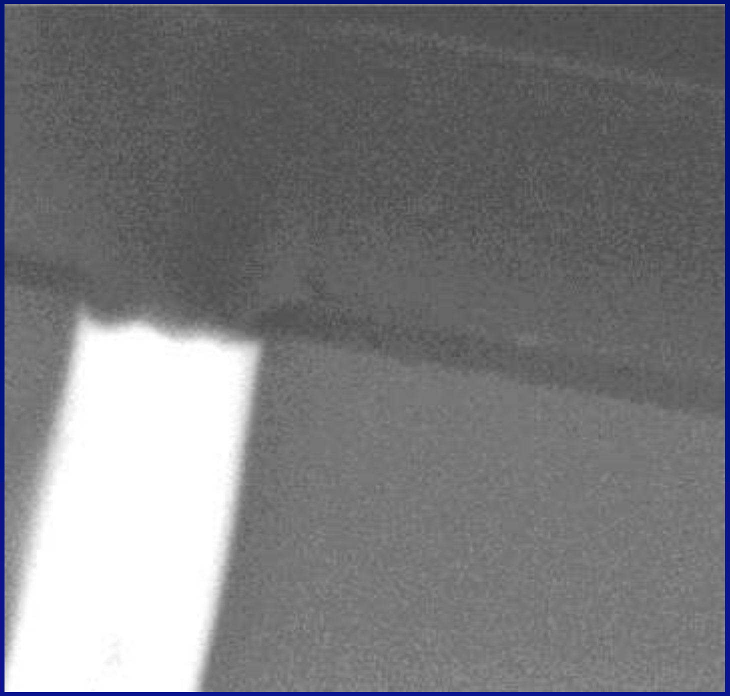


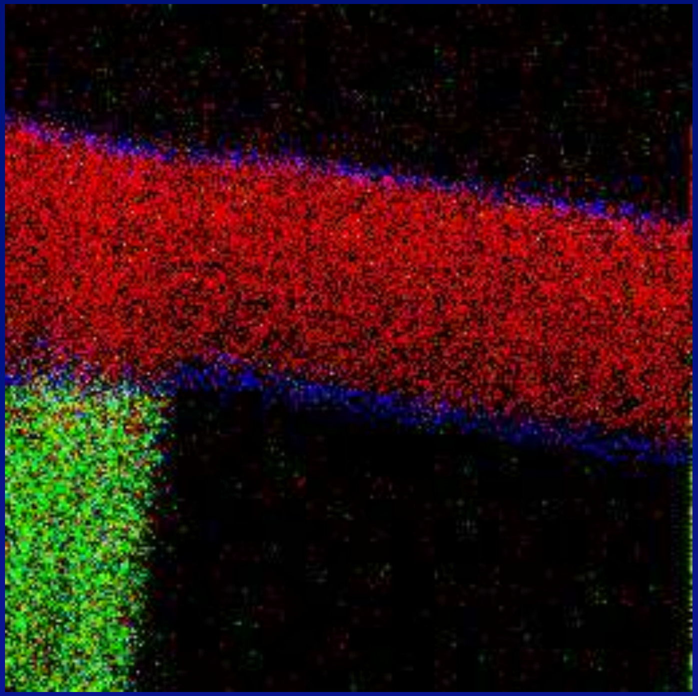
EDS spectrum of interconnect



EDS spectra at 30 KeV on thin films samples have very low Bremsstrahlung backgrounds.

STEM-in-SEM X-ray maps





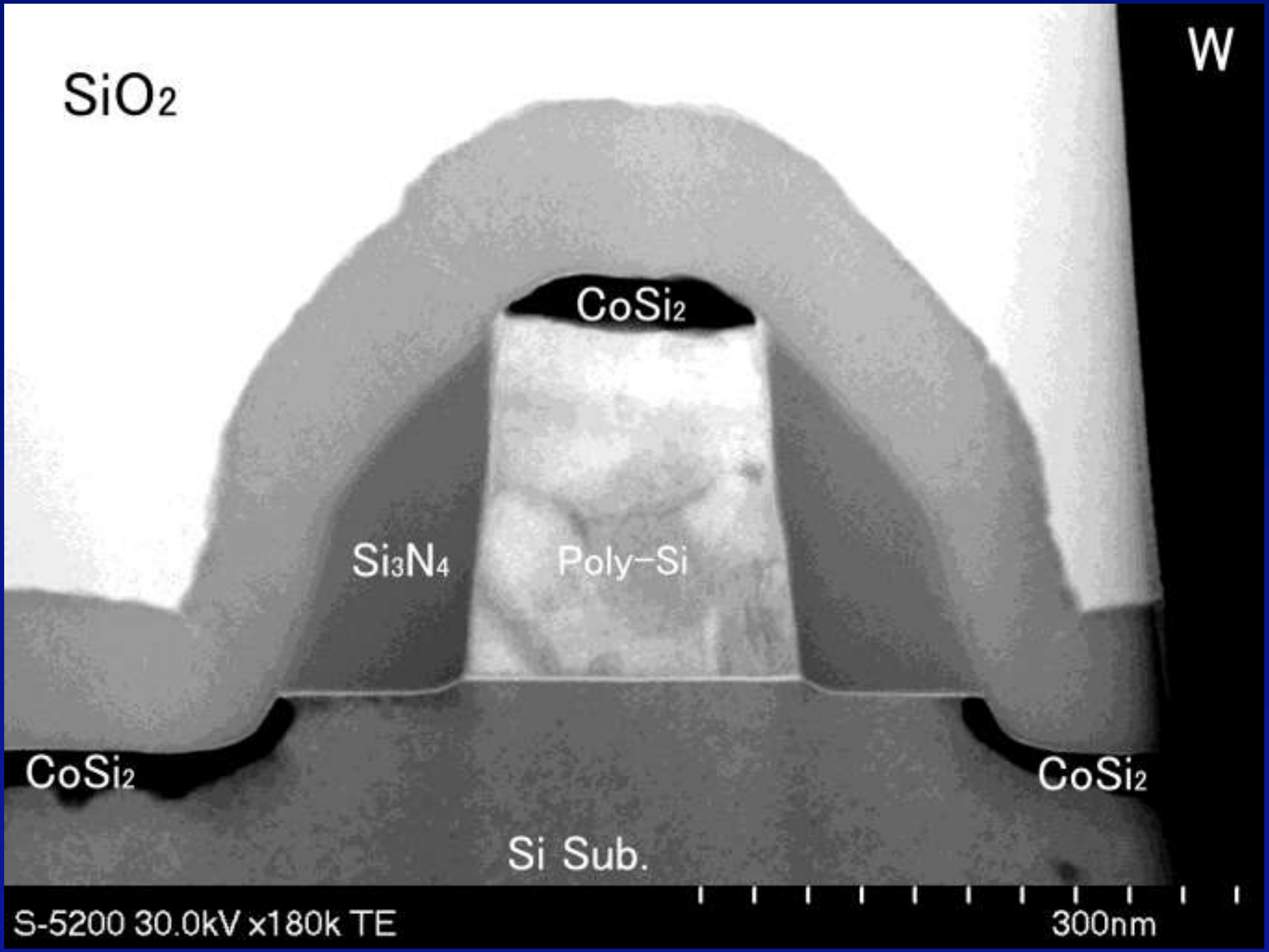
400 nm

SEM image Mag = 75,000x

X-ray maps: W L-α
Al K-α
Ti L-α

STEM-in-SEM X-ray maps show approximately 10 nm lateral spatial resolution, compared to 100 nm or greater for standard SEM x-ray maps.

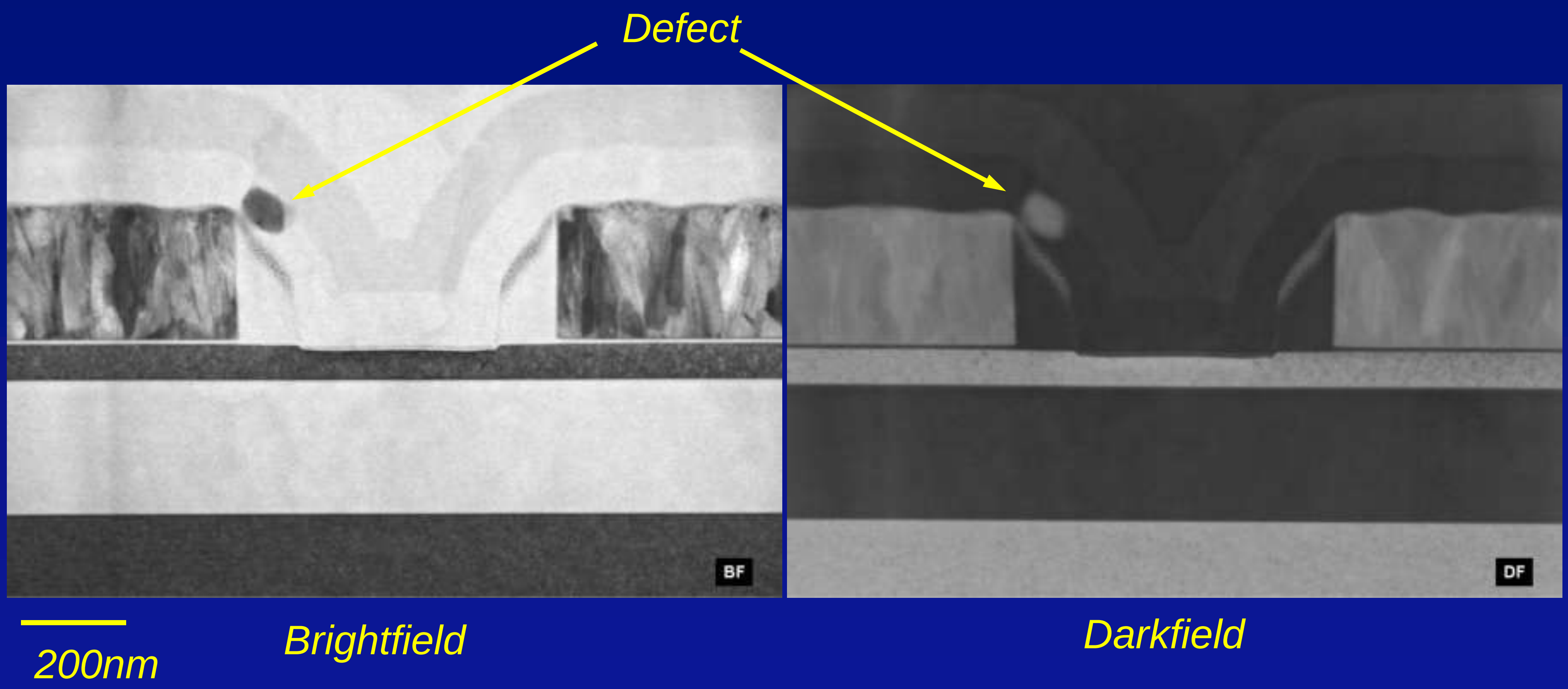
STEM-in-SEM with a dedicated detector



150 nm **Mag = 200,000 x**

Bryan Tracy, ISTFA 2002

In-situ STEM Imaging in a Dual-beam SEM/FIB system



Brightfield *Darkfield*

STEM image @ 30kV with a dedicated STEM detector
P. Gnauck, et al., ISTFA 2003 Proceedings, p. 132.

Advantages of STEM-in-SEM over TEM

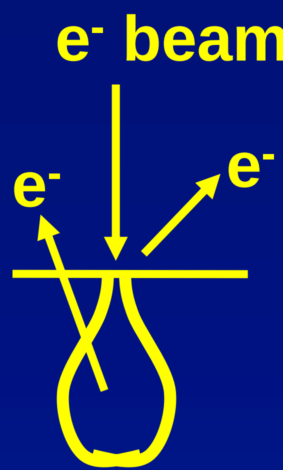
- Cheap and widely available
- Not limited by 3 mm sample size
- EDS at very high spatial resolution which is not possible with many TEMs.

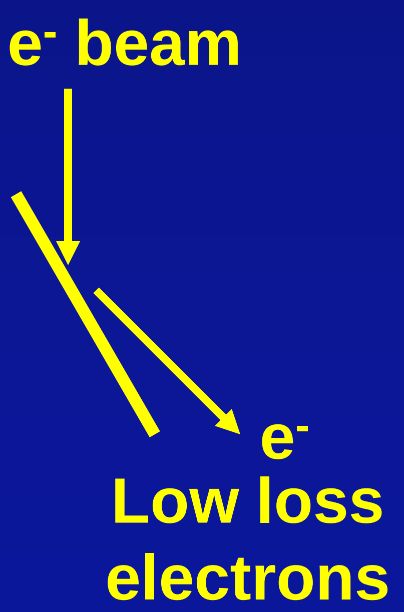
Ultra-high resolution SEM

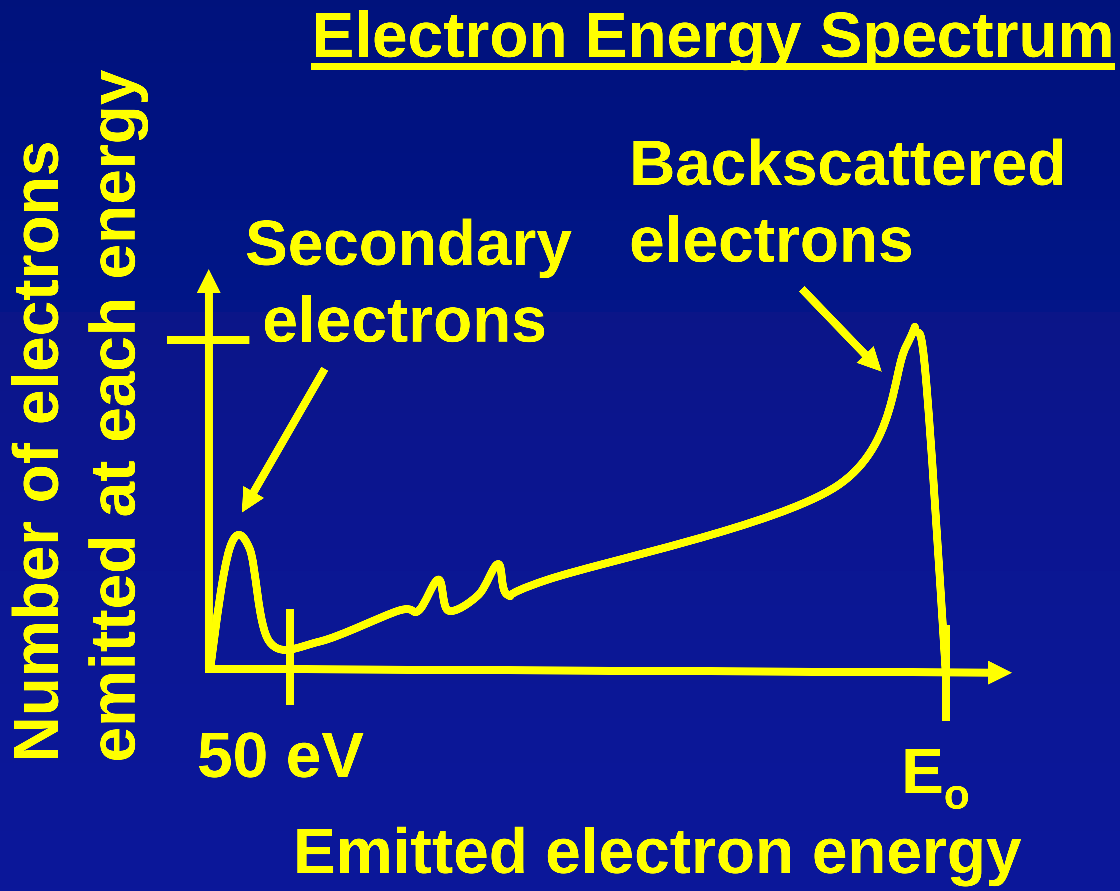
Part 2:

Forward scattered electron imaging in the SEM

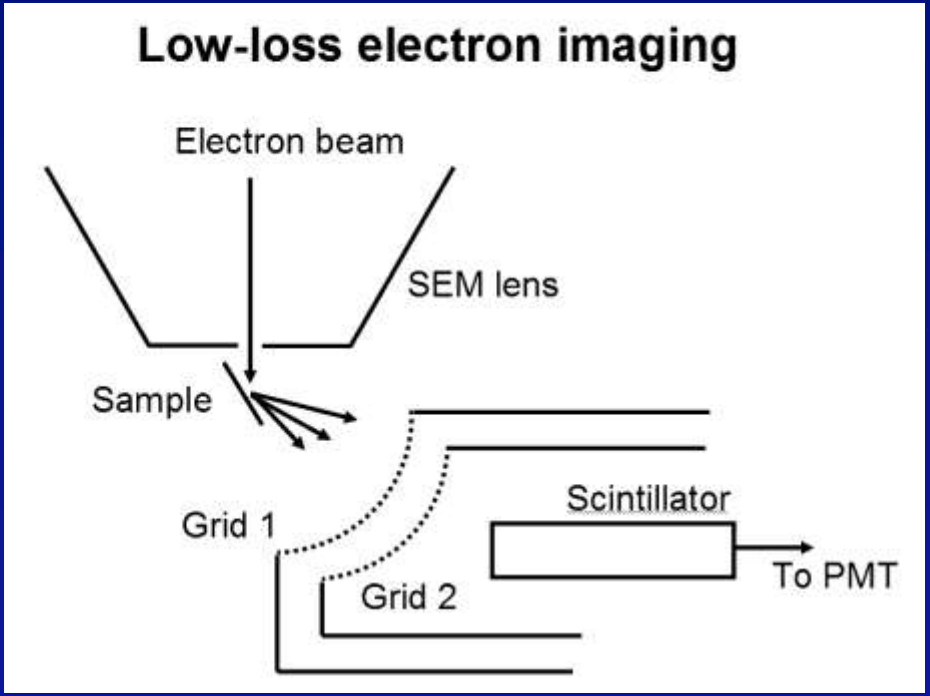
An old idea – low loss imaging

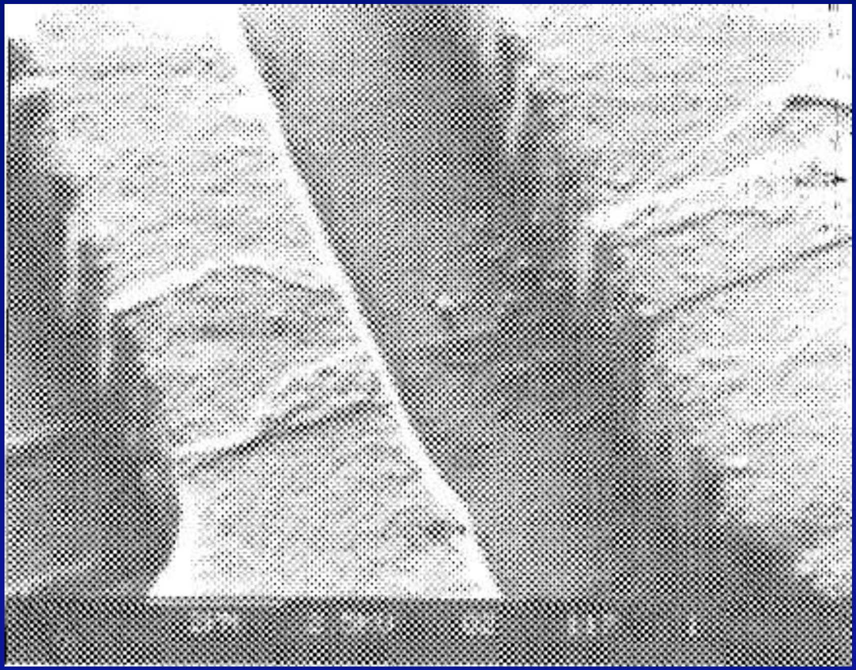






Low loss electron imaging



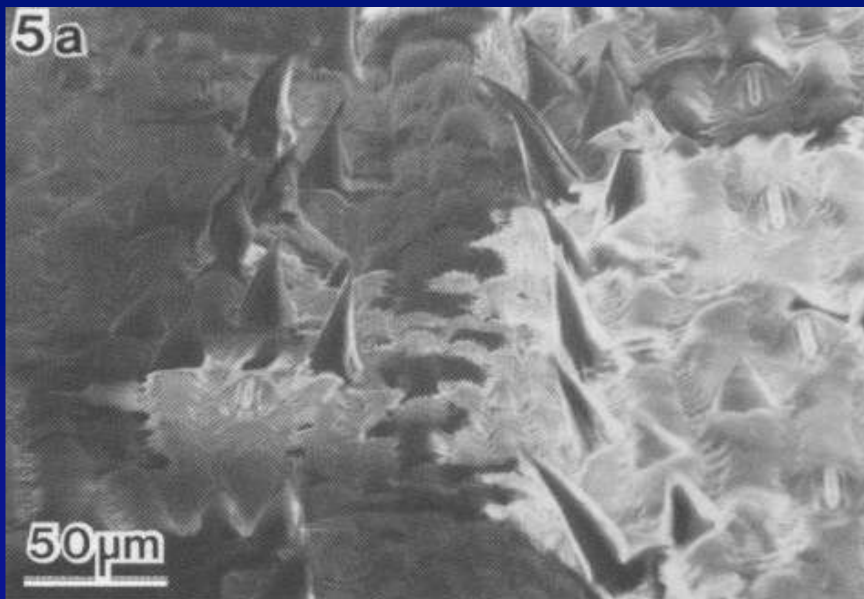


2 μm ——— Mag = 10,000 x

Wells, 1971

Secondary electron vs. low-loss electron imaging

Secondary electron image



50 µm ——— Mag = 400 x

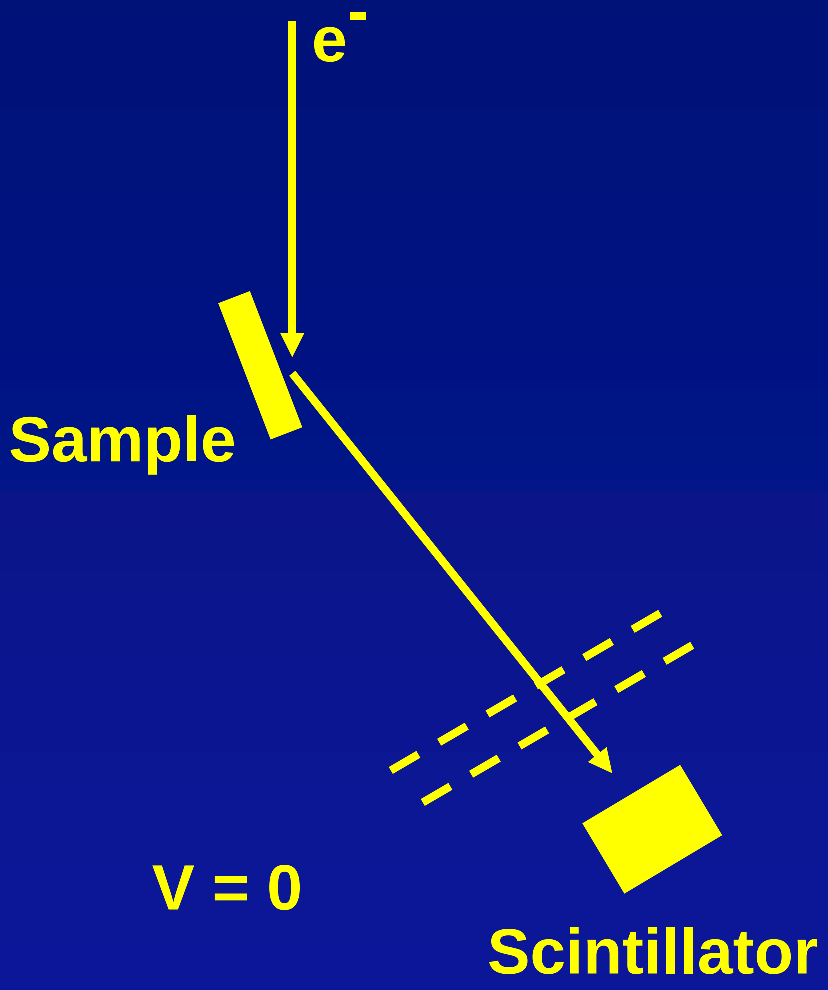
Low-loss electron image

50 µm ——— Mag = 400 x

Mature leaf blade abaxial surface showing cuticular ridges on bulliform cells between rows of epidermal hairs

Wells, 1989

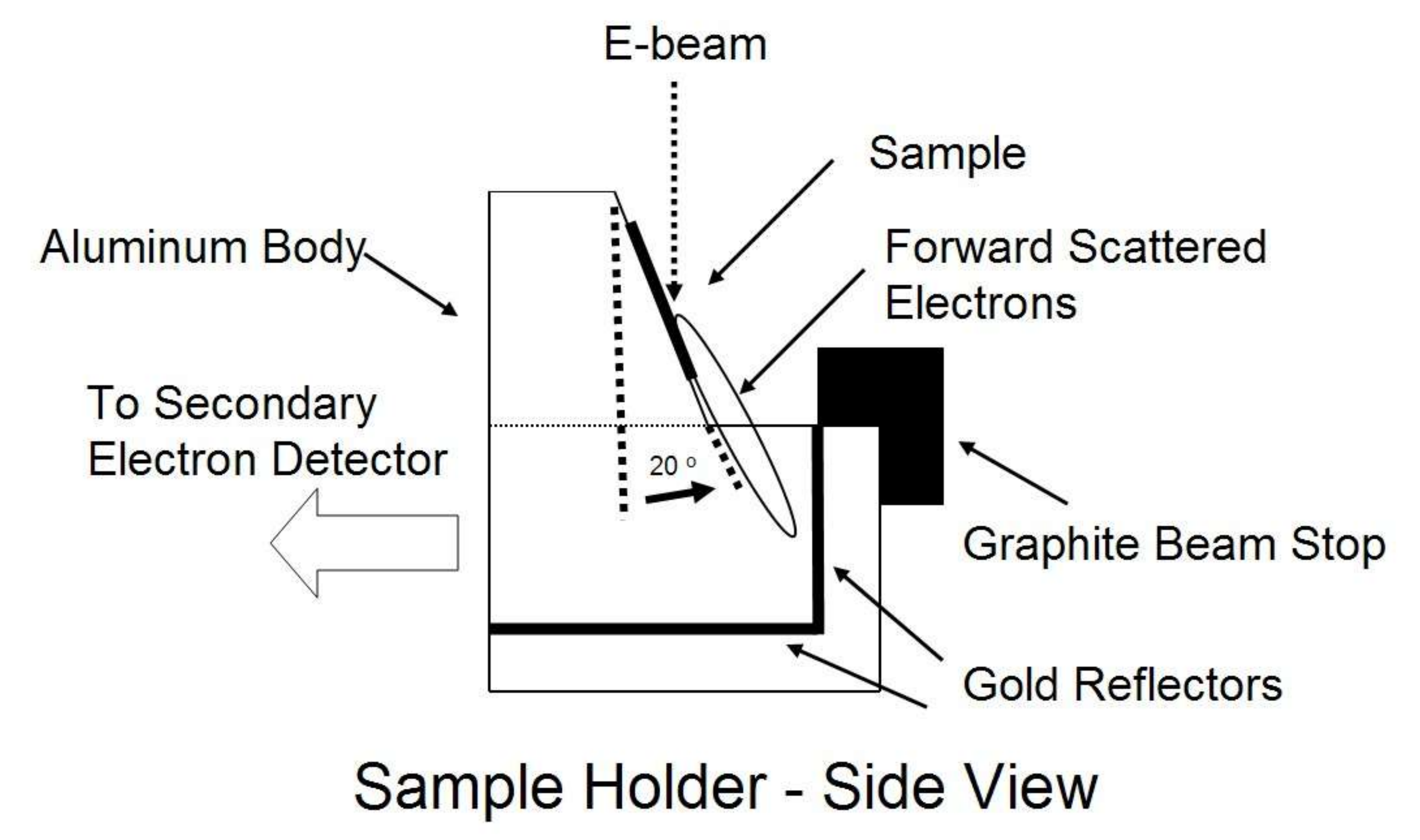
Low loss electron imaging



25 nm —   Mag = 350,000 x

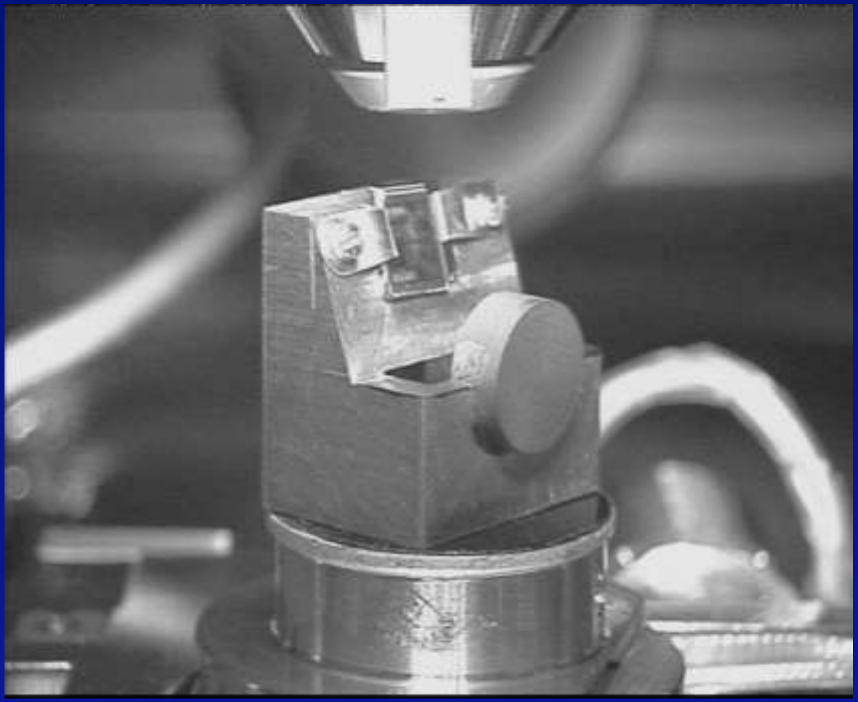
Broers, 1974

Forward scattered electron imaging



Vanderlinde, 2003

Forward scattered electron imaging



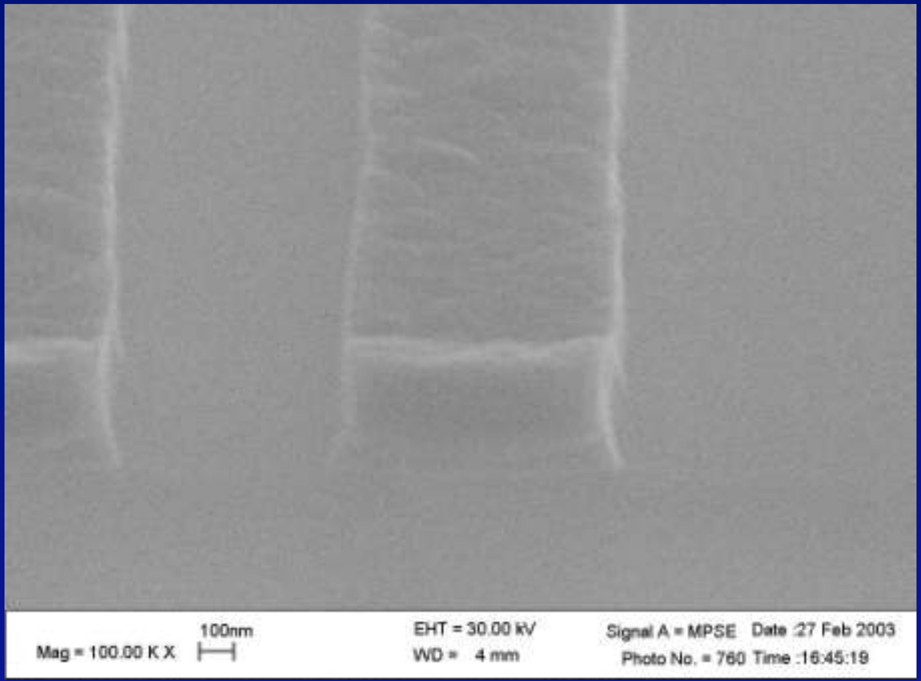
Front View

Rear View

Vanderlinde, 2003

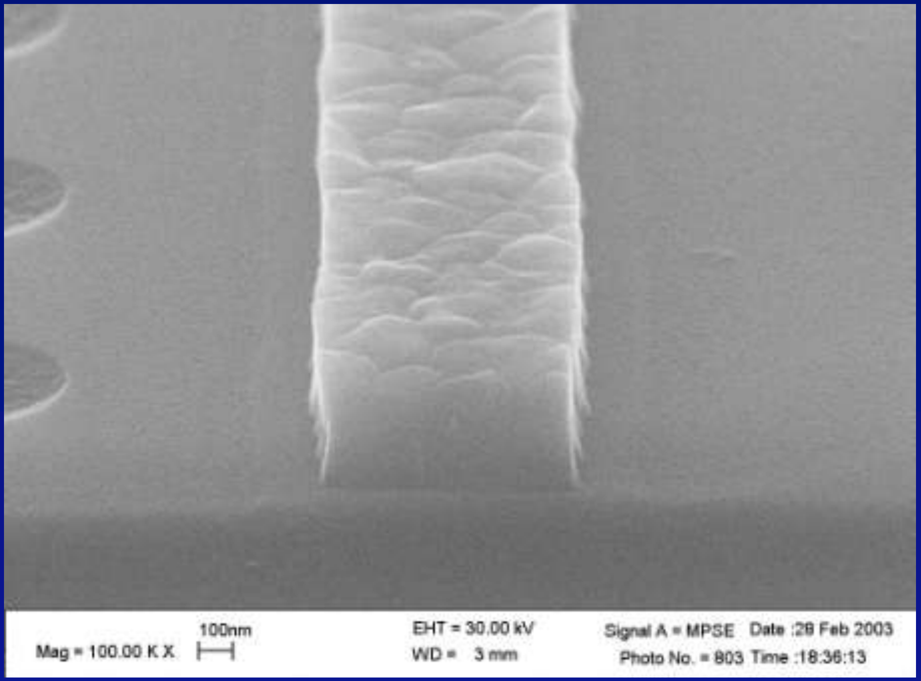
Secondary electron vs. forward scattered electron imaging

Secondary electron image



0.1 µm – Mag = 100,000 x

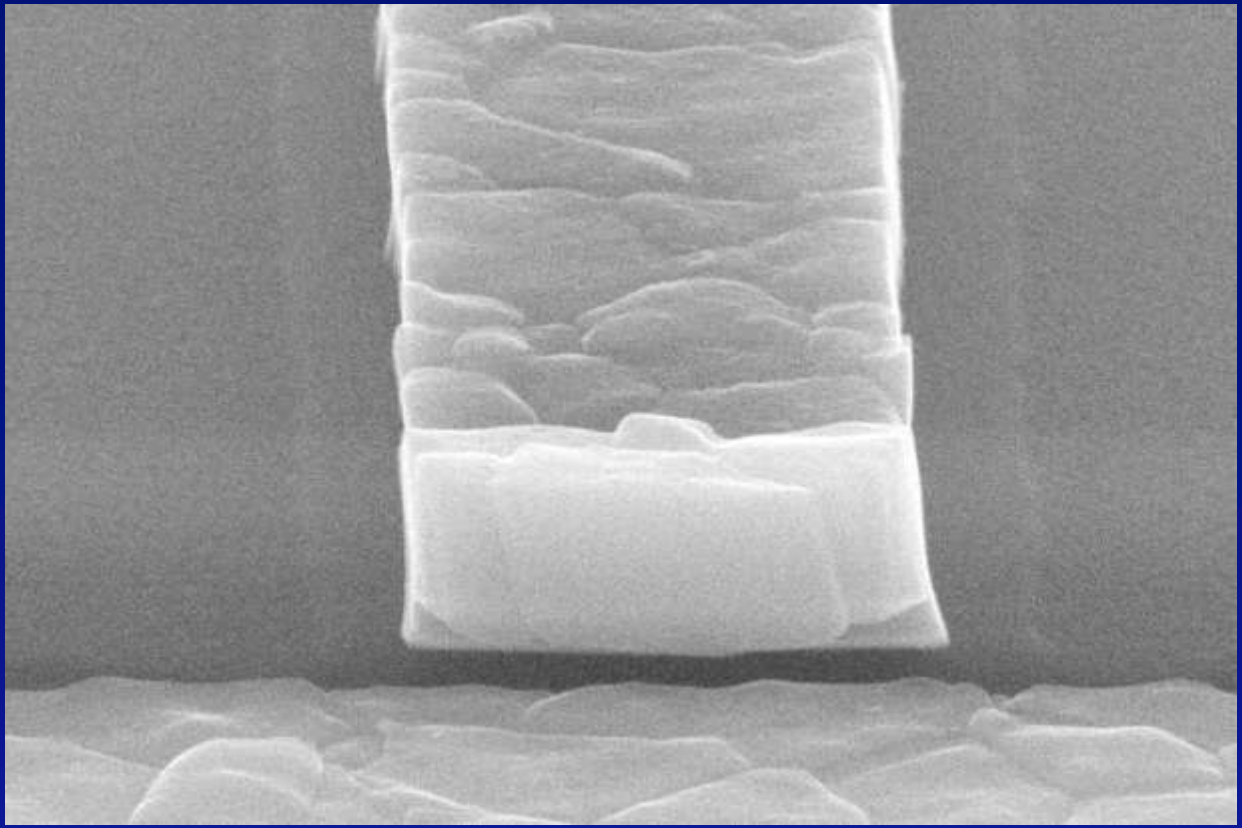
Forward scattered image



0.1 µm – Mag = 100,000 x

Uncoated poly-silicon
30 kV beam energy

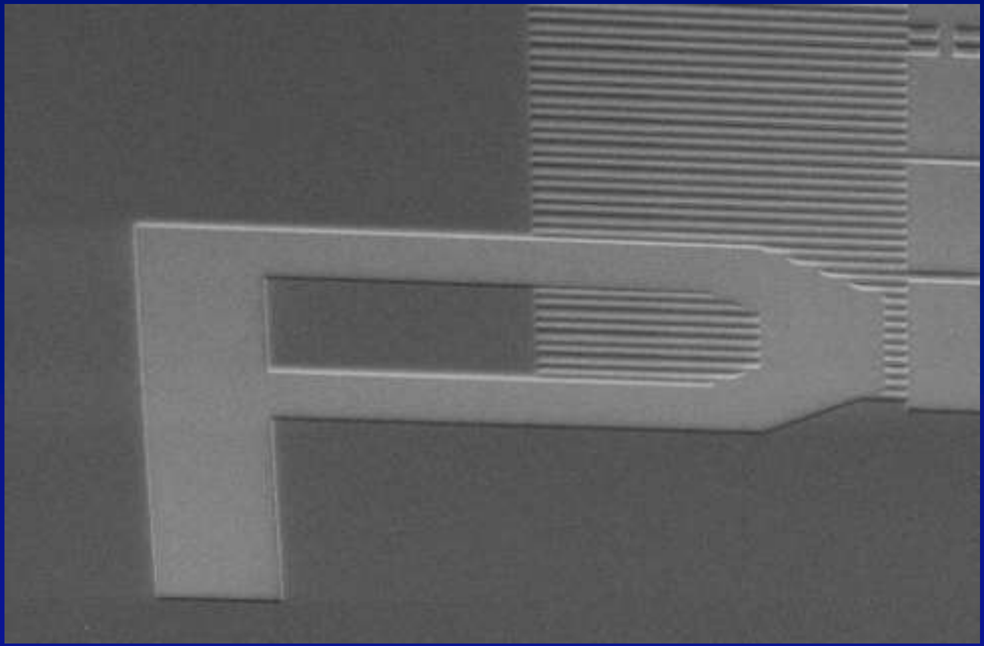
Forward scattered imaging with dynamic focus



— 100 nm   Mag = 100,000x

Imaging using Dynamic Focus.
<u>Uncoated</u> sample imaged at <u>30 KV</u> beam voltage.

Forward scattered imaging – image correction



– 10 μm Mag = 850x

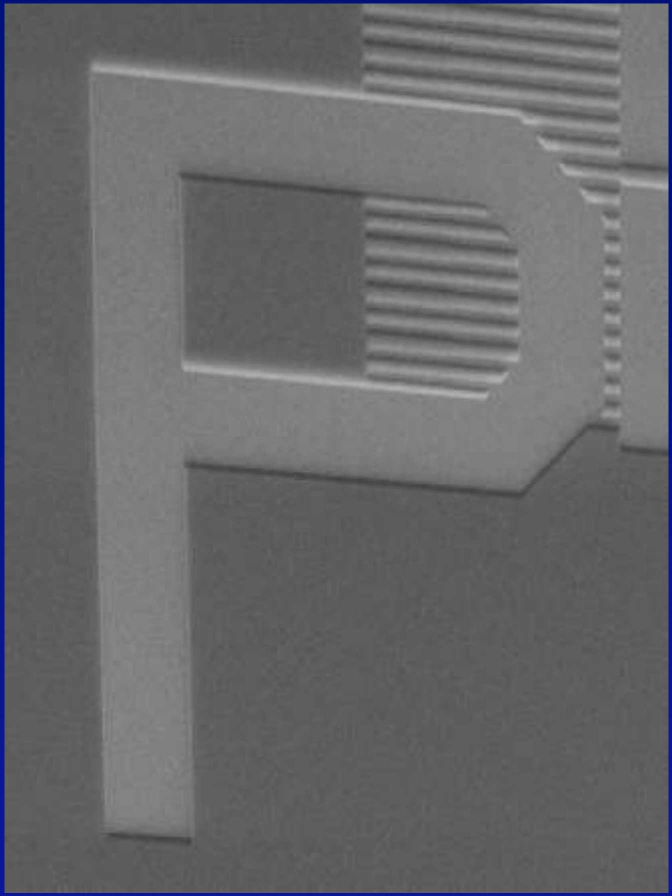
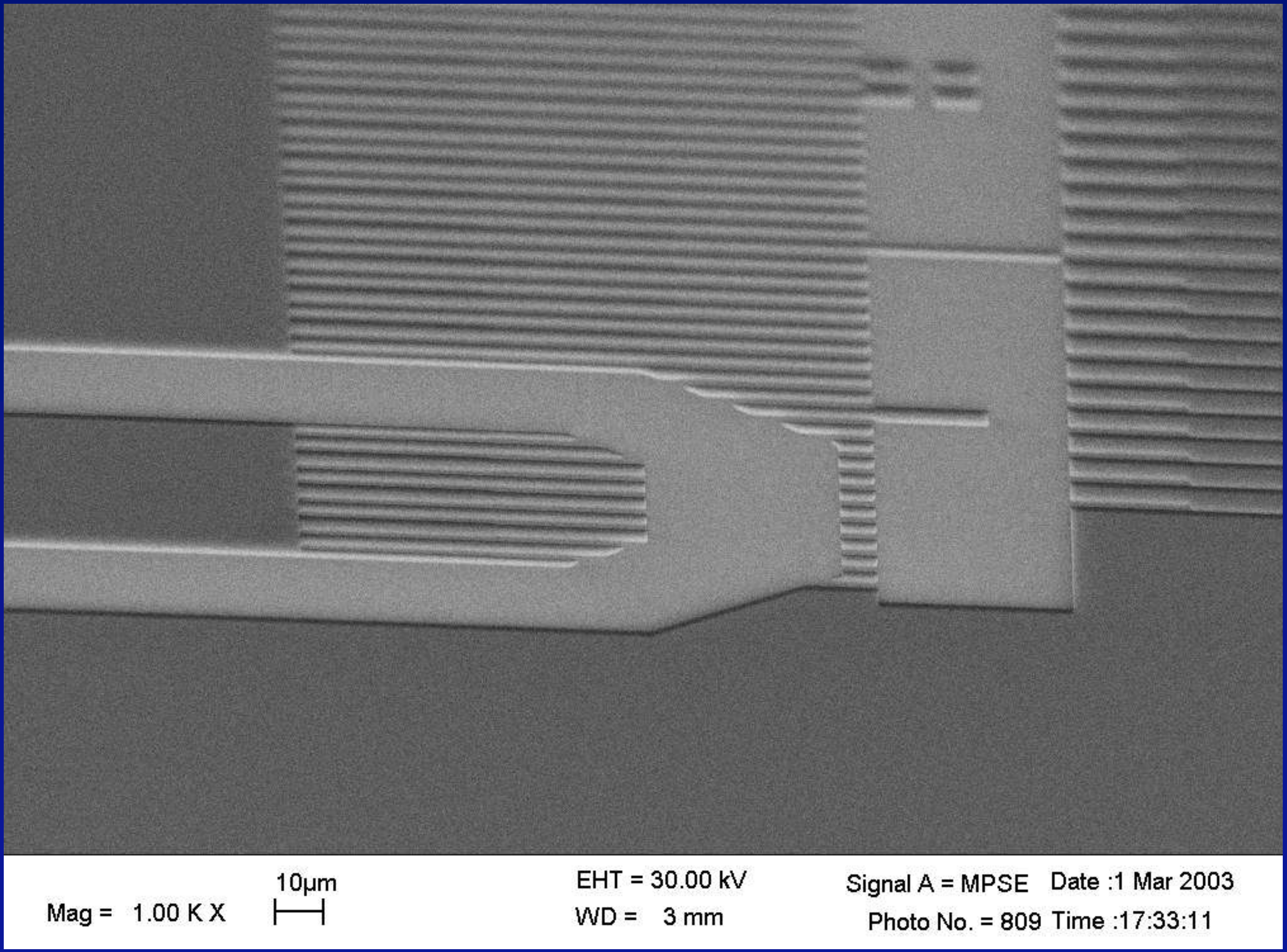


Photo-resist before (left) and after (right) image correction.
Uncoated sample imaged at 30 KV beam voltage.

Forward scattered electron imaging

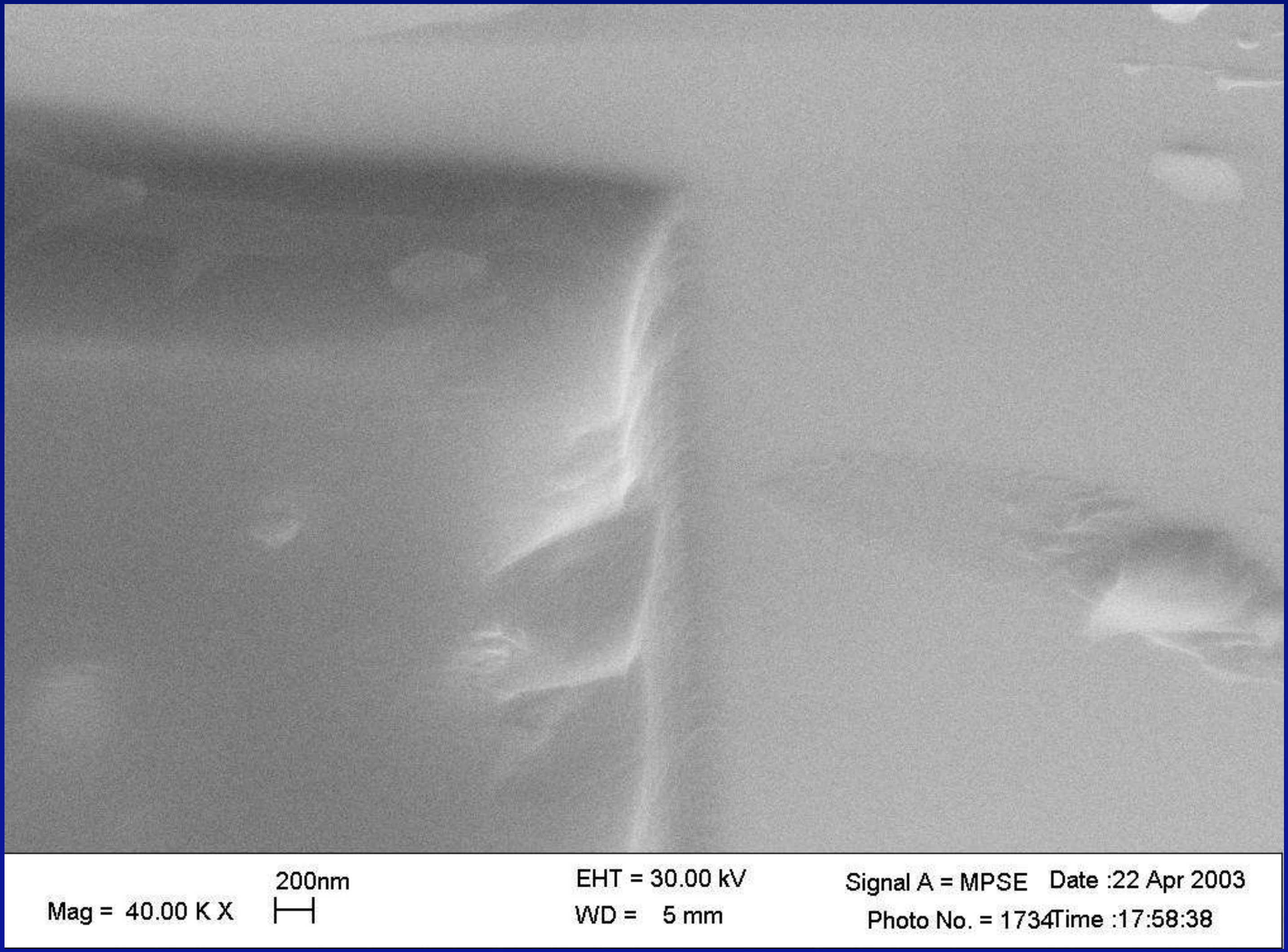
Uncoated photo-resist (often charges in SEM)



10 µm — **Mag = 1,000 x**

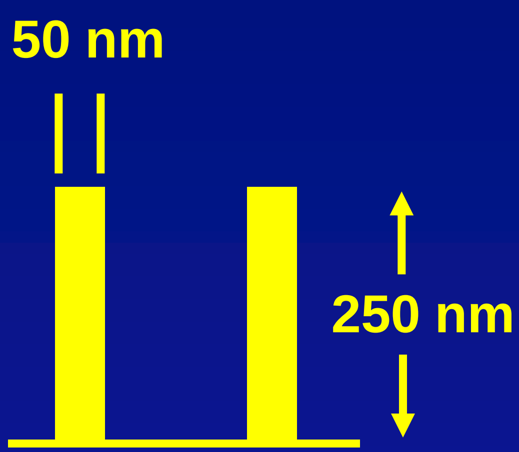
Forward scattered electron imaging

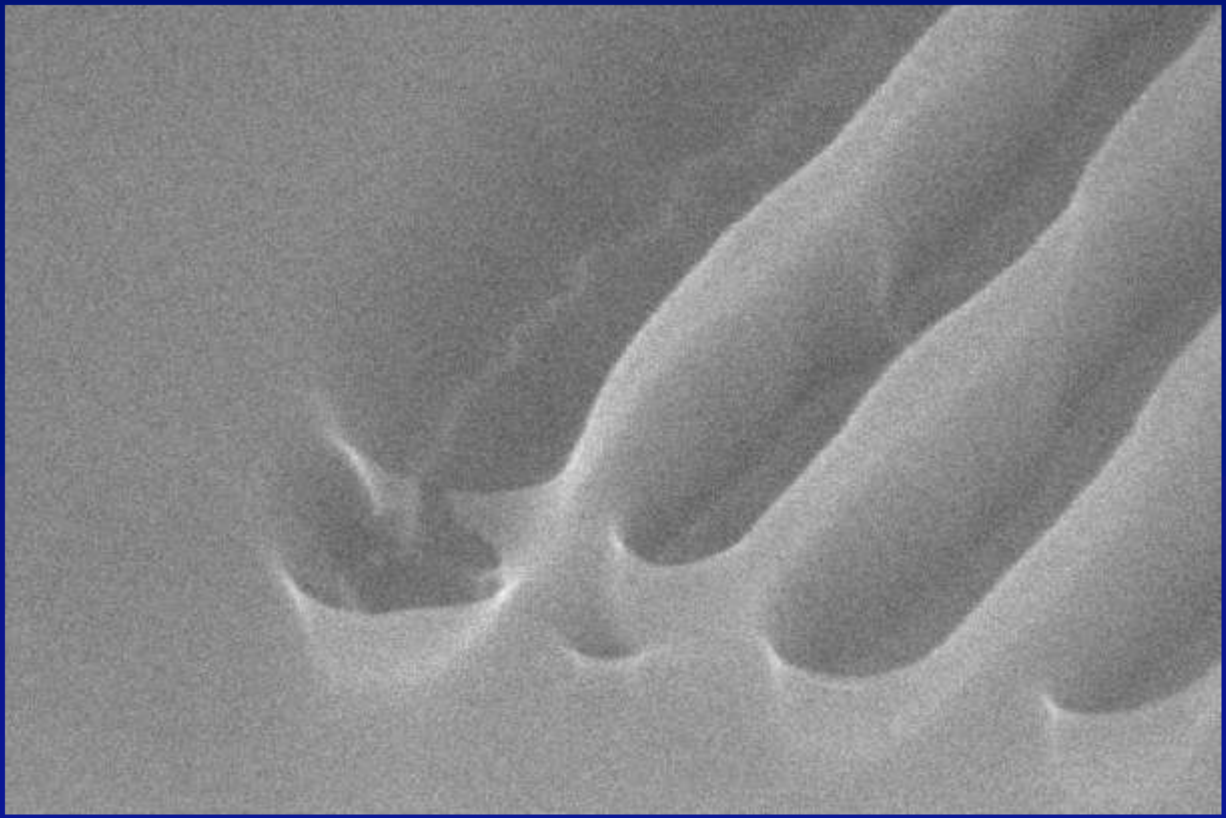
Uncoated photo-resist (often charges in SEM)



0.5 µm — **Mag = 40,000 x**

Forward scattered imaging – e-beam resist





— 50 nm   Mag = 200,000x

E-beam resist (PMMA) lines 250 nm high by 50 nm wide.
<u>Uncoated</u> sample imaged at <u>30 kV</u> beam voltage.

Discussion

• Contrast is based on scattering of the high energy electrons toward the detector, similar to dark-field STEM.

• Collecting the low-loss electrons by capturing a small solid angle of the forward scattered beam produces excellent images.

• An energy filter is not required for high resolution imaging.

Conclusions

• Forward scattered electron imaging is a practical technique for improved imaging in an unmodified SEM.

• Forward scattered electron imaging eliminates charging on uncoated insulators even at 30 KV.

• Forward scattered electron imaging is especially well suited for low atomic number materials.

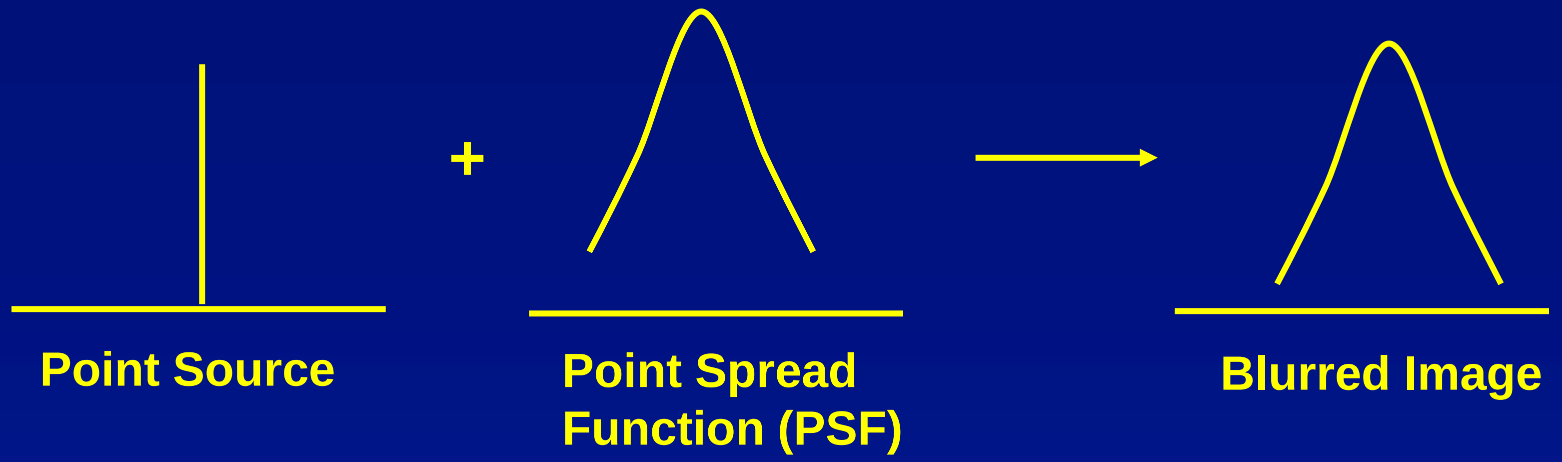
• Dynamic focus and image correction can compensate for the high tilt angle.

Ultra-High resolution SEM

Part 3:

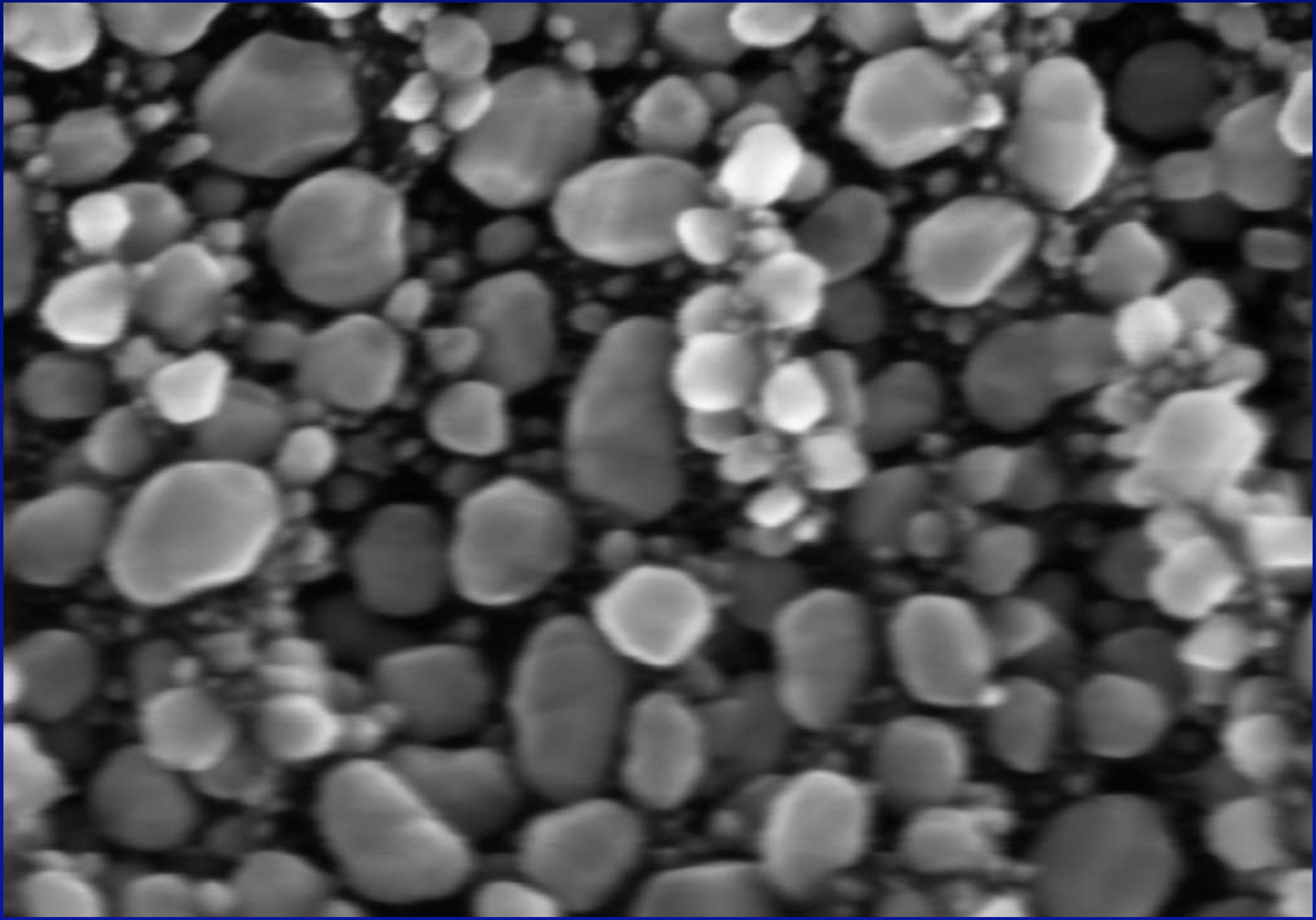
Blind Deconvolution in the SEM

Blind deconvolution of SEM images



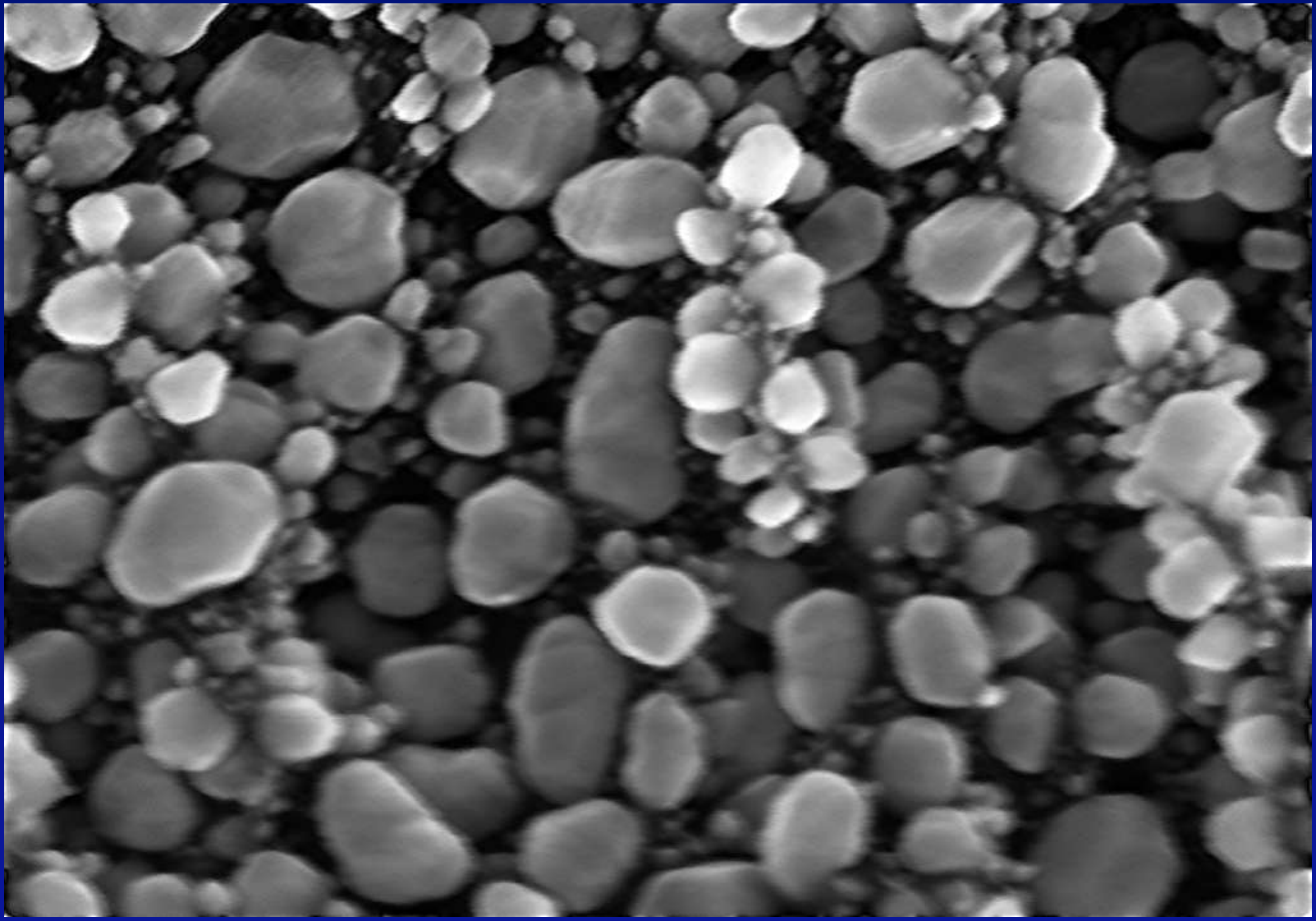
- Deconvolves PSF blur from the image
- NOT the same as "sharpening" features found in common graphics programs
- Not previously done with SEM images
- Requires 16-bit TIFF images with S/N = 120:1 (10 minute scans)

Gold island sample- Before



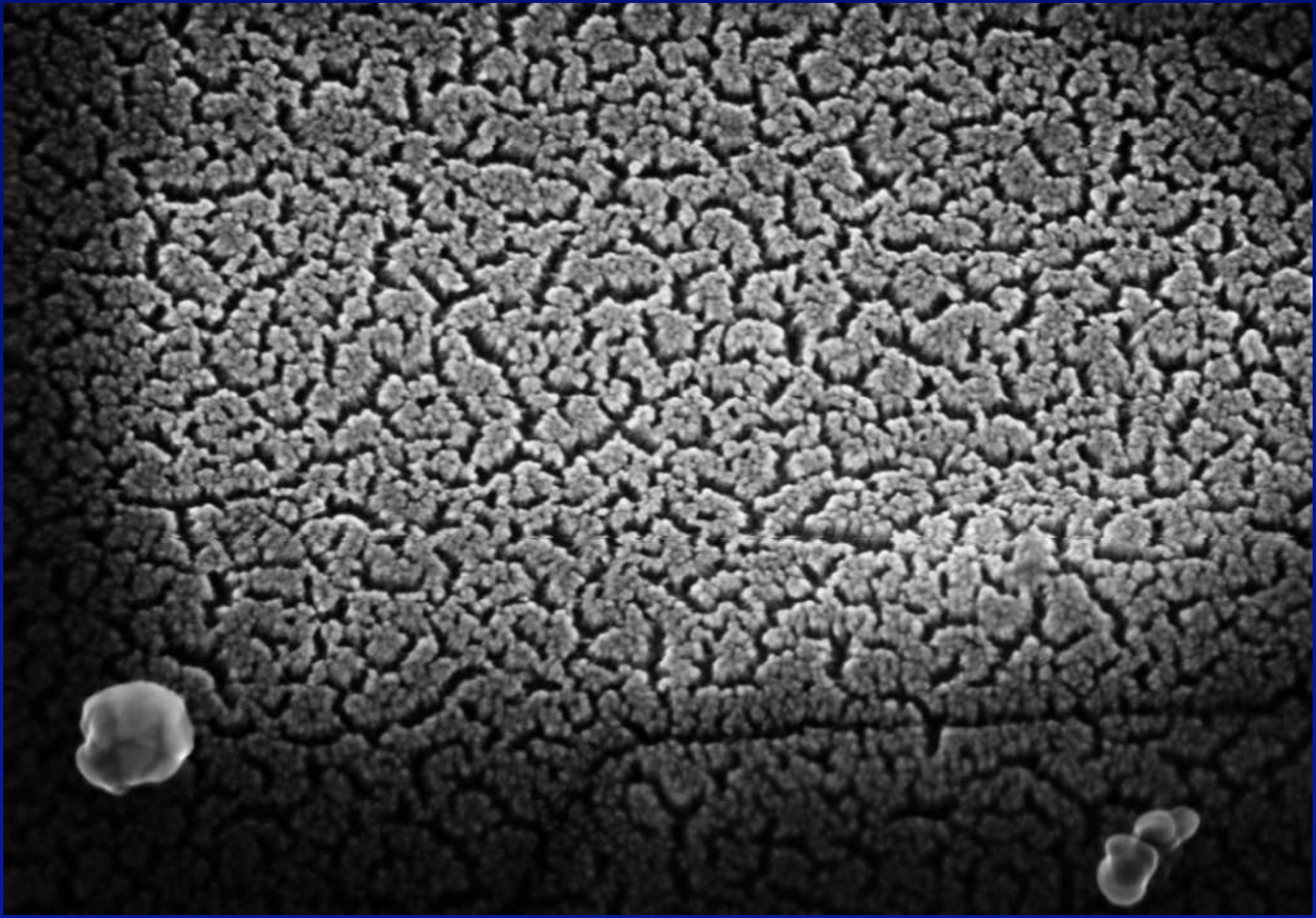
20 nm Mag = 500,000X

Gold island sample - After



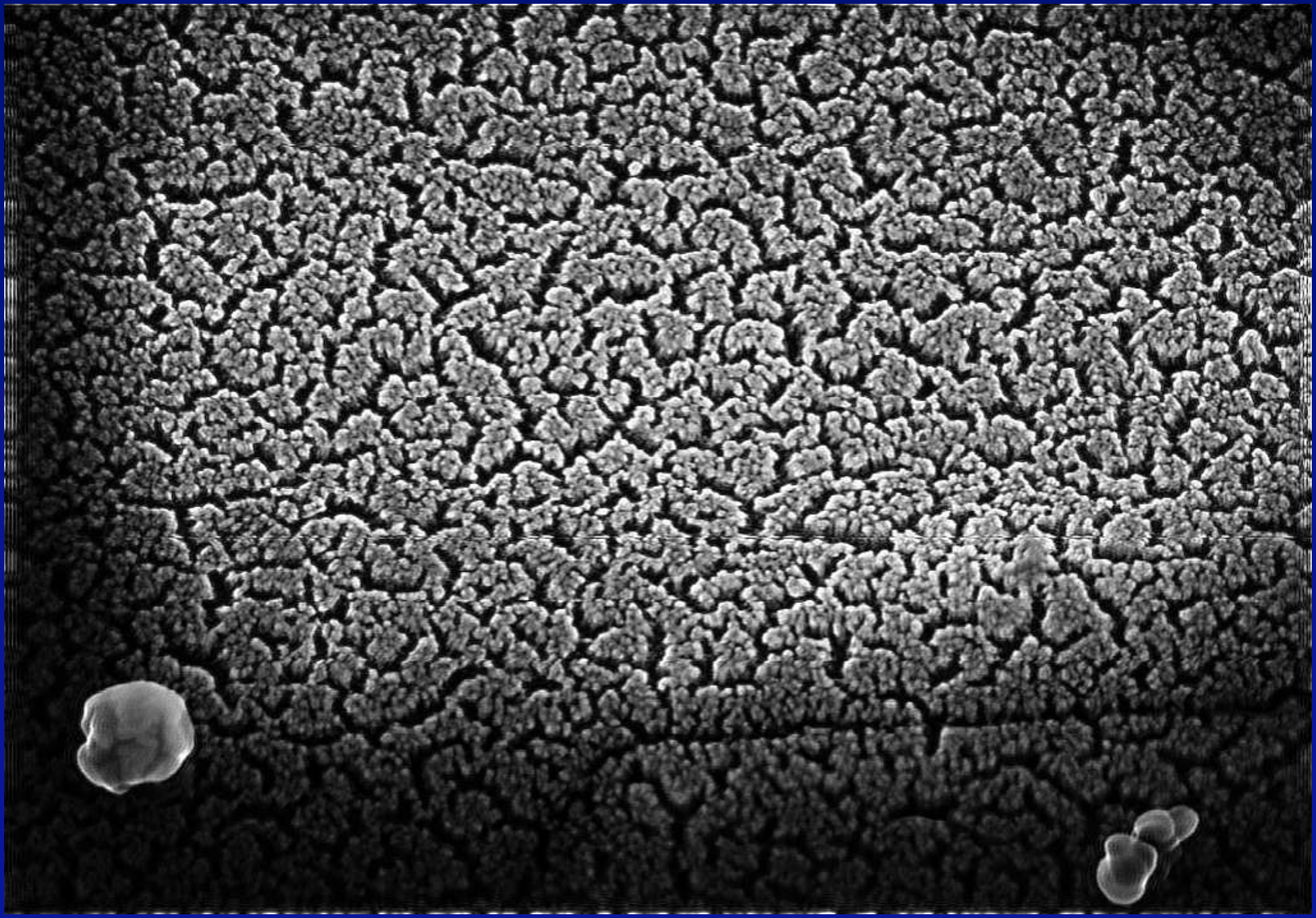
20 nm Mag = 500,000X

Sputter coating sample - Before



50 nm Mag = 200,000X

Sputter coating sample - After



50 nm Mag = 200,000X

Ultra-High resolution SEM

Part 4:

Helium Ion Microscopy

Helium Ion Microscopy

Beam of He^+ ions used as a probe

Sub-nm spot size

Strong topographic contrast

http://www.smt.zeiss.com/nts

Helium Ion Optical Column

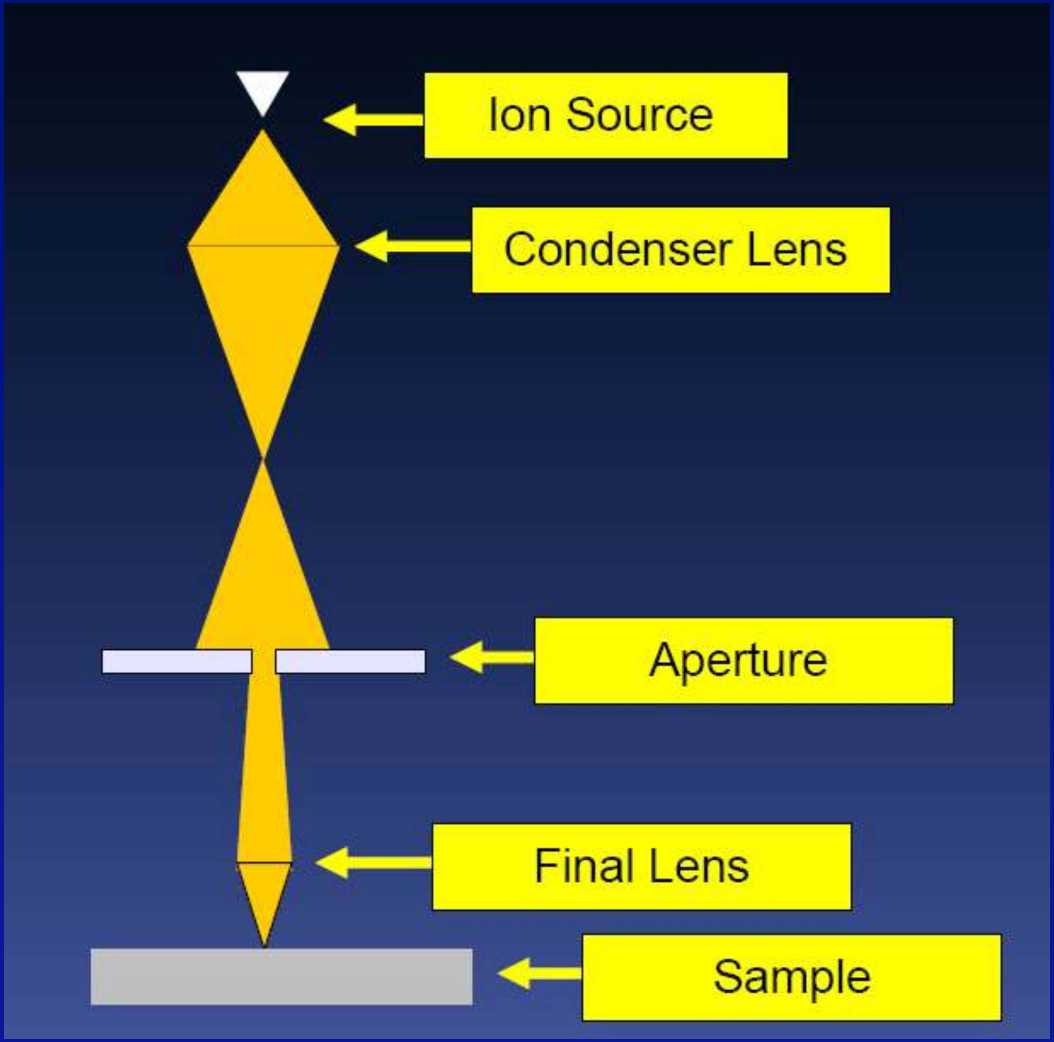


Image courtesy Carl Zeiss Nano Technology Systems Division

Helium Ion Source

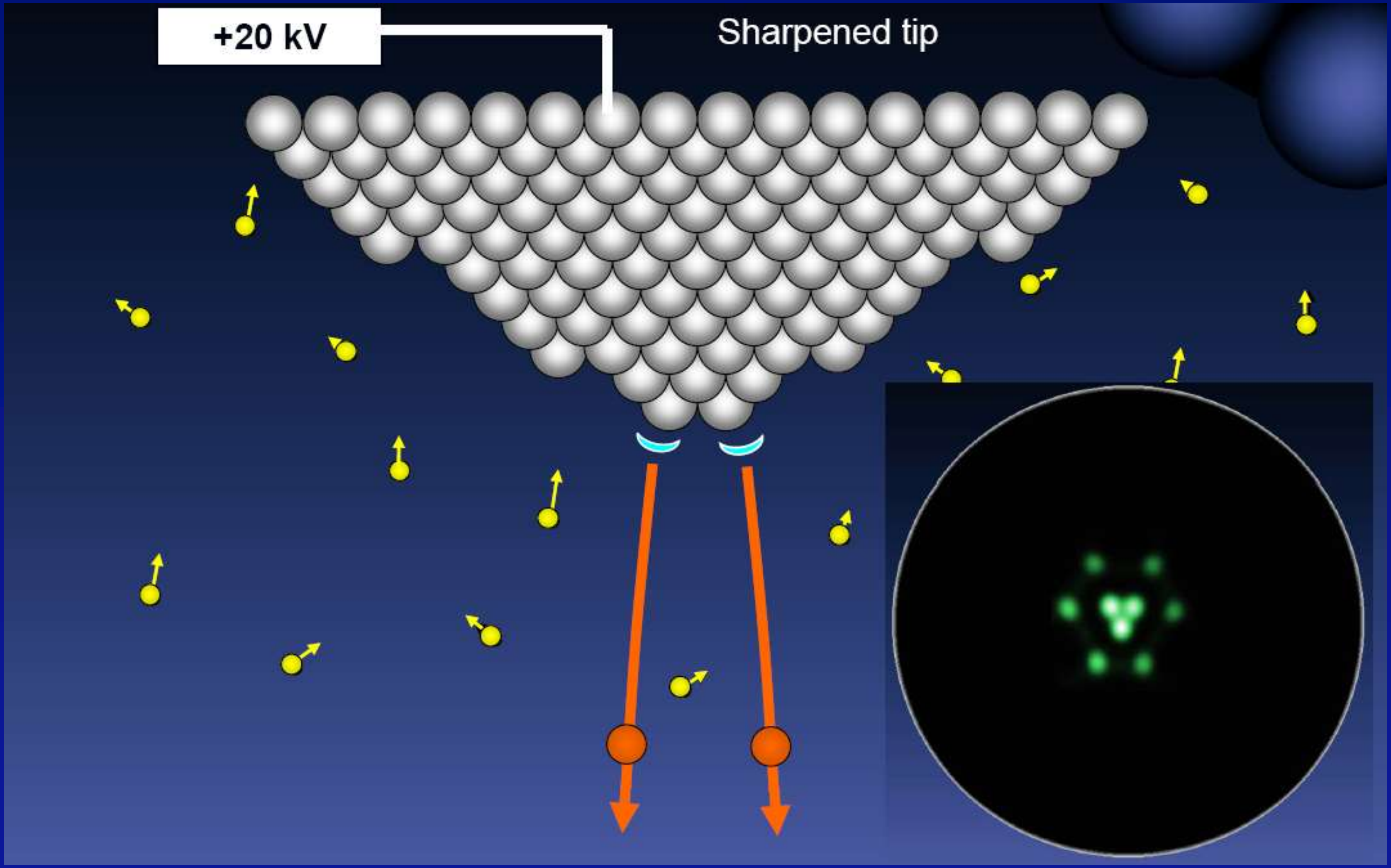


Image courtesy Carl Zeiss Nano Technology Systems Division

Helium Ion Source

- High Brightness > 3×10^9 A/cm^2-Sr
- Small virtual source size (sub-Angstrom?)
- Low energy spread (~ 0.5 eV) gives reduced chromatic aberration
- He ion has small de Broglie wavelength for reduced diffraction effects compared to SEM

Data courtesy Carl Zeiss Nano Technology Systems Division

Helium Ion Source

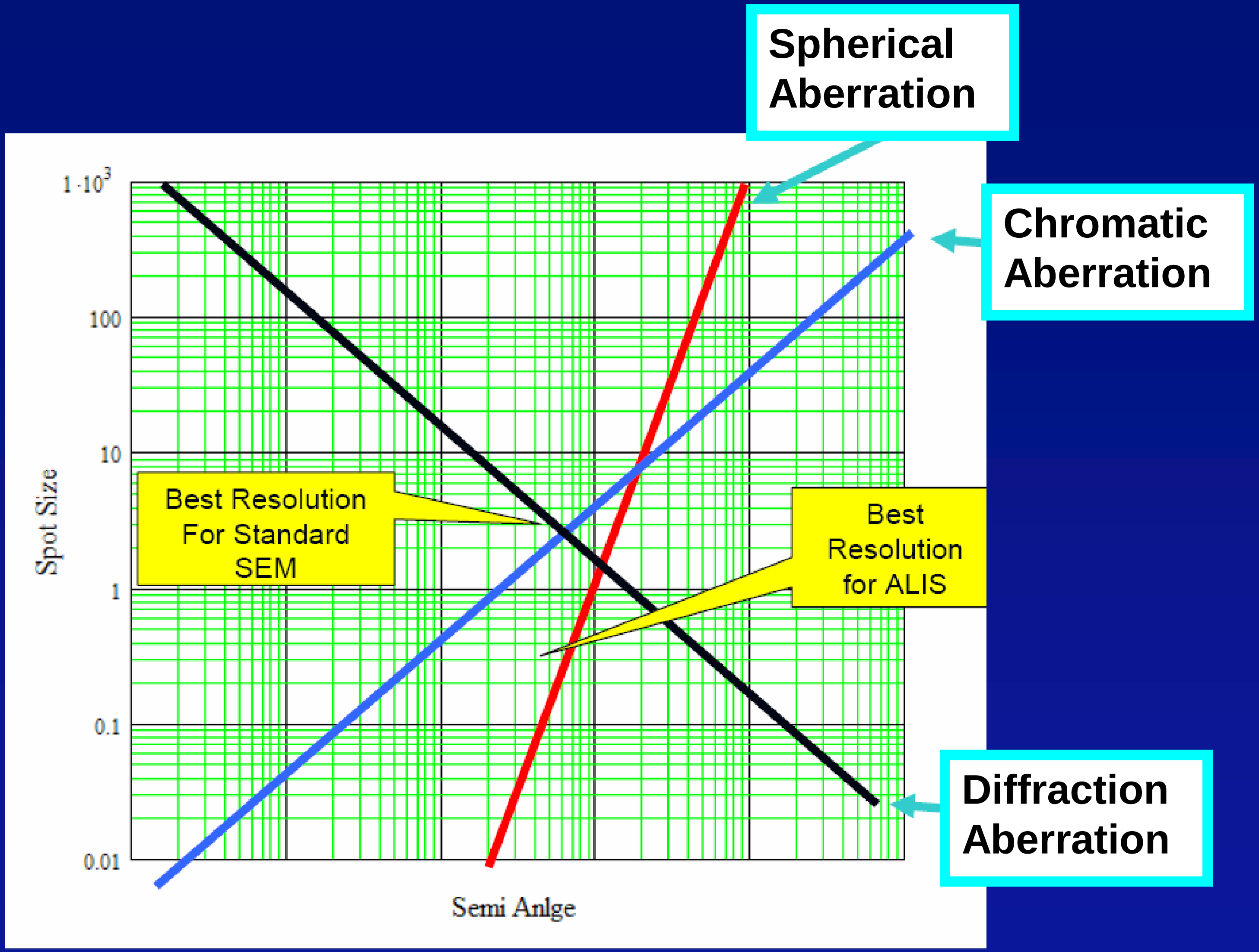
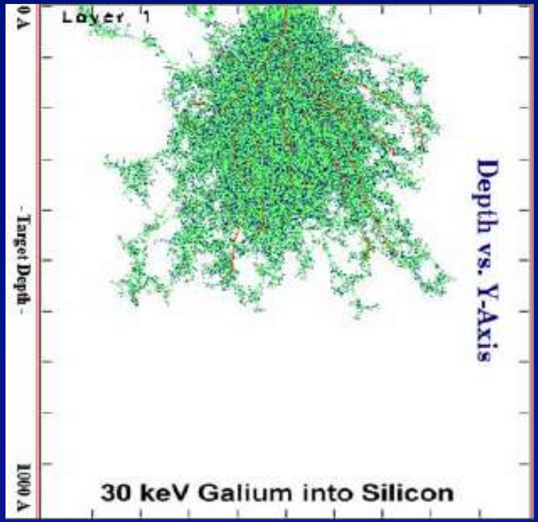


Image courtesy Carl Zeiss Nano Technology Systems Division

Interaction Volumes

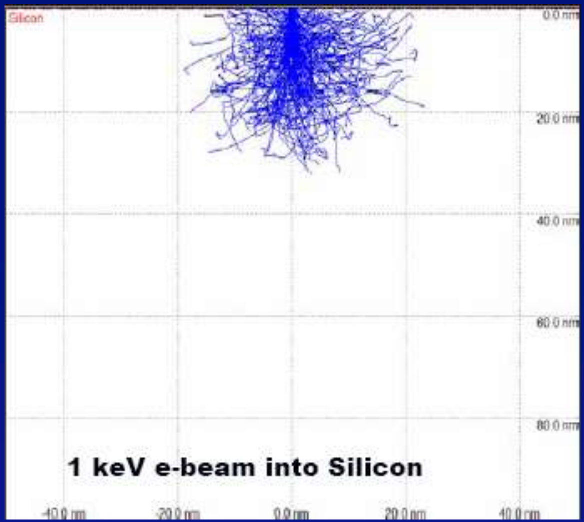
Gallium FIB



30 keV Gallium in Si

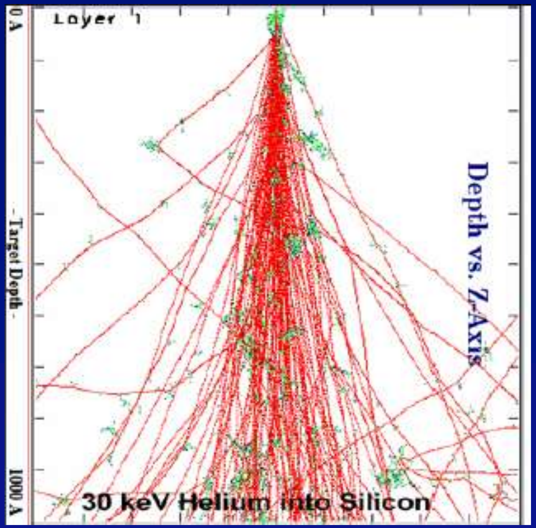
100 nm

Standard SEM



1 keV electrons in Si

Helium FIB



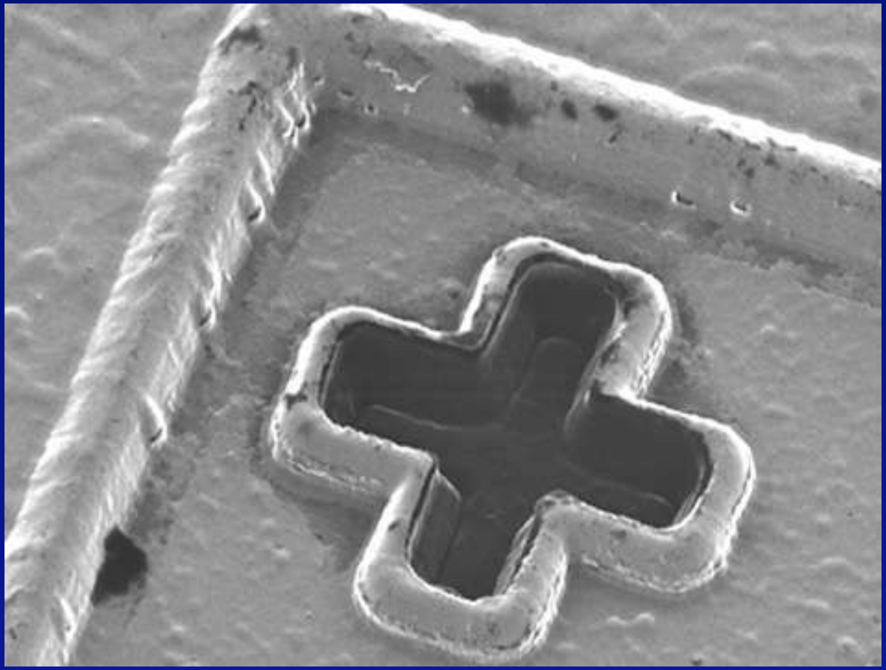
30 keV Helium in Si

30 keV Gallium and 1 keV electrons have a large interaction volume at the surface. He ions are well collimated beyond the secondary electron escape depth.

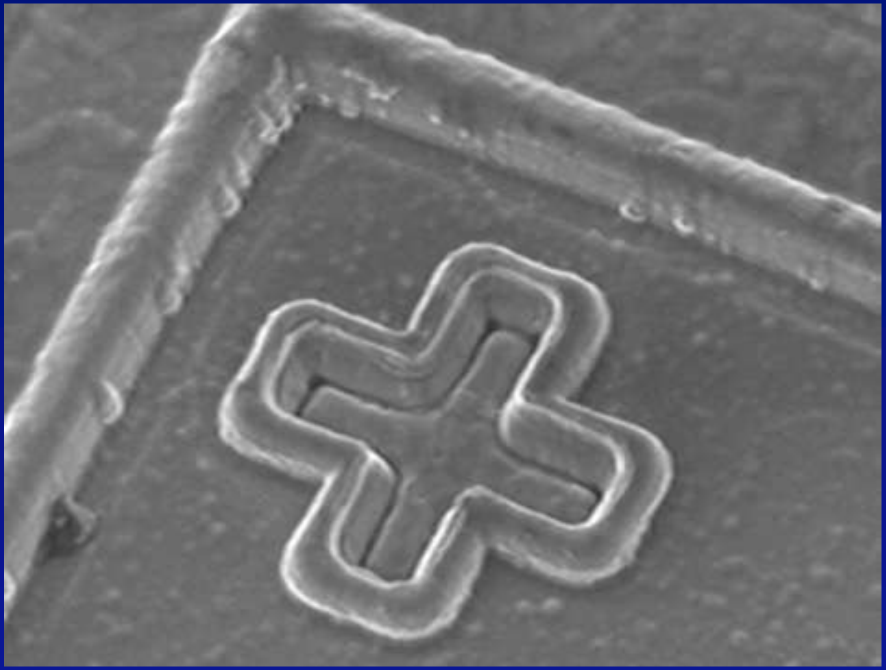
Images courtesy Carl Zeiss Nano Technology Systems Division

Helium Ion SE Imaging

Strong material contrast



He ion induced secondary electron image



Electron microscope secondary electron image

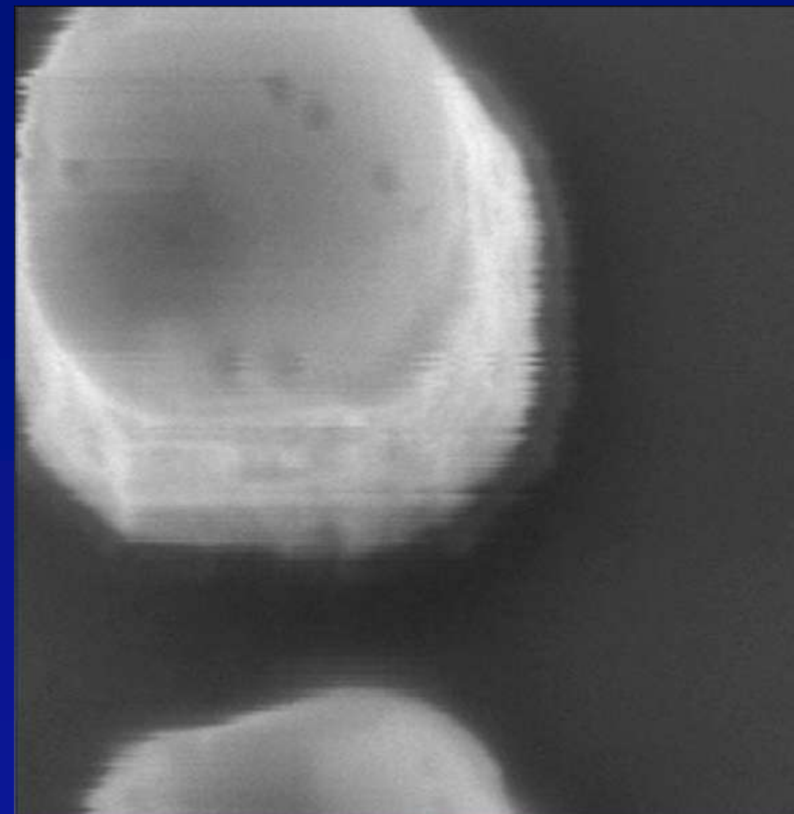
Images courtesy Carl Zeiss Nano Technology Systems Division

Helium Ion SE Imaging

High Resolution – aluminum post on silicon at ~150,000x

1 micron FOV

He ion induced secondary electron image

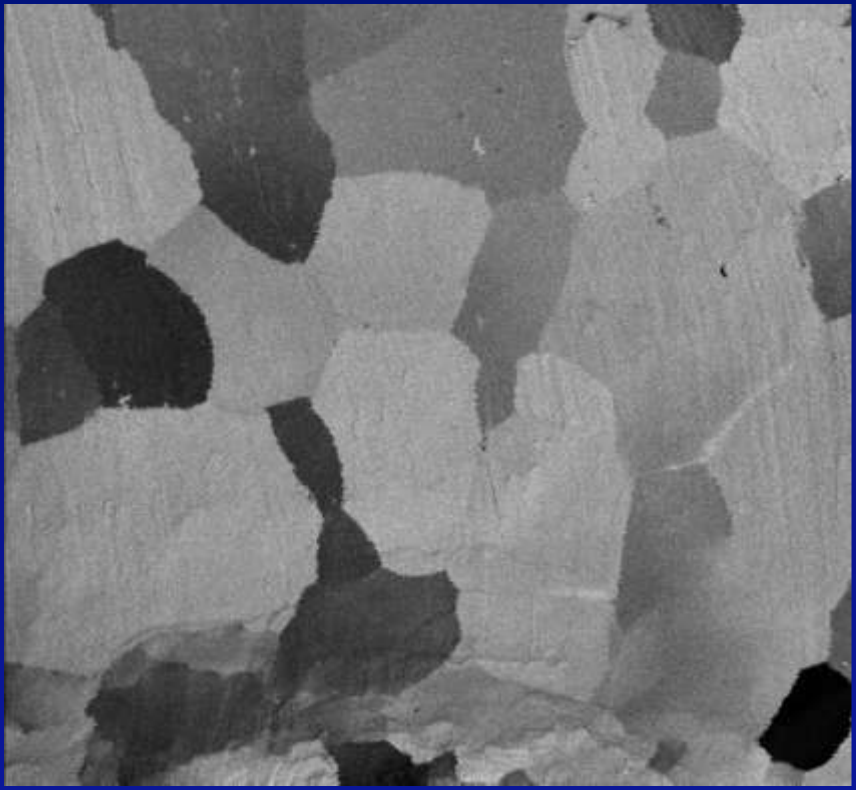


Electron microscope secondary electron image

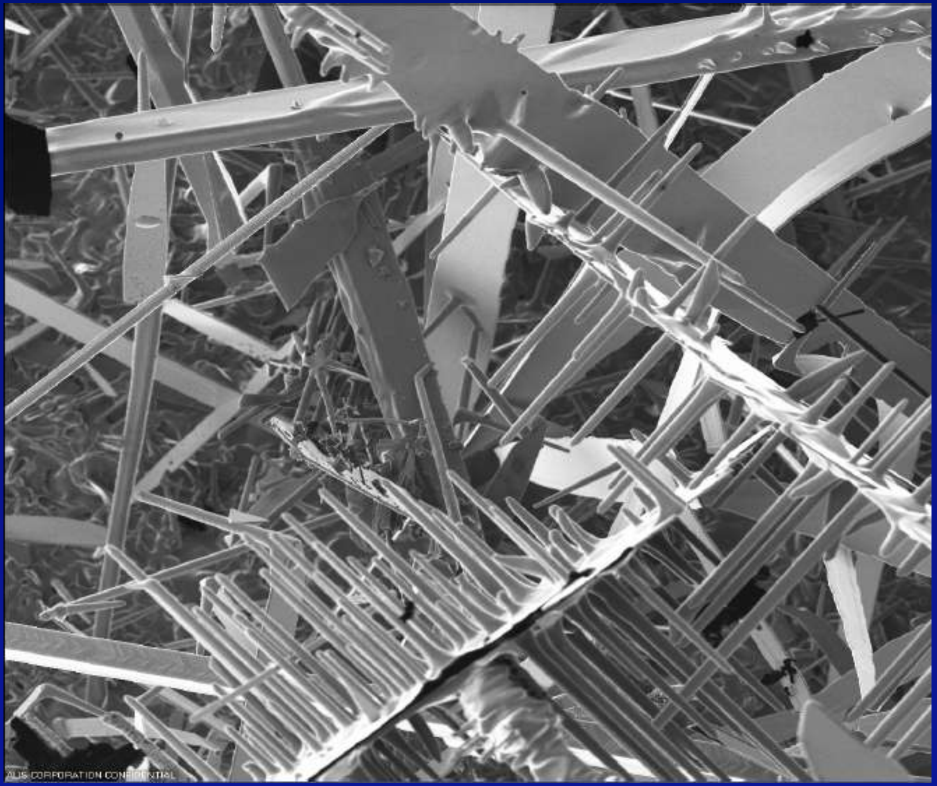
Images courtesy Carl Zeiss Nano Technology Systems Division

Helium Ion SE Imaging

Crystallographic information



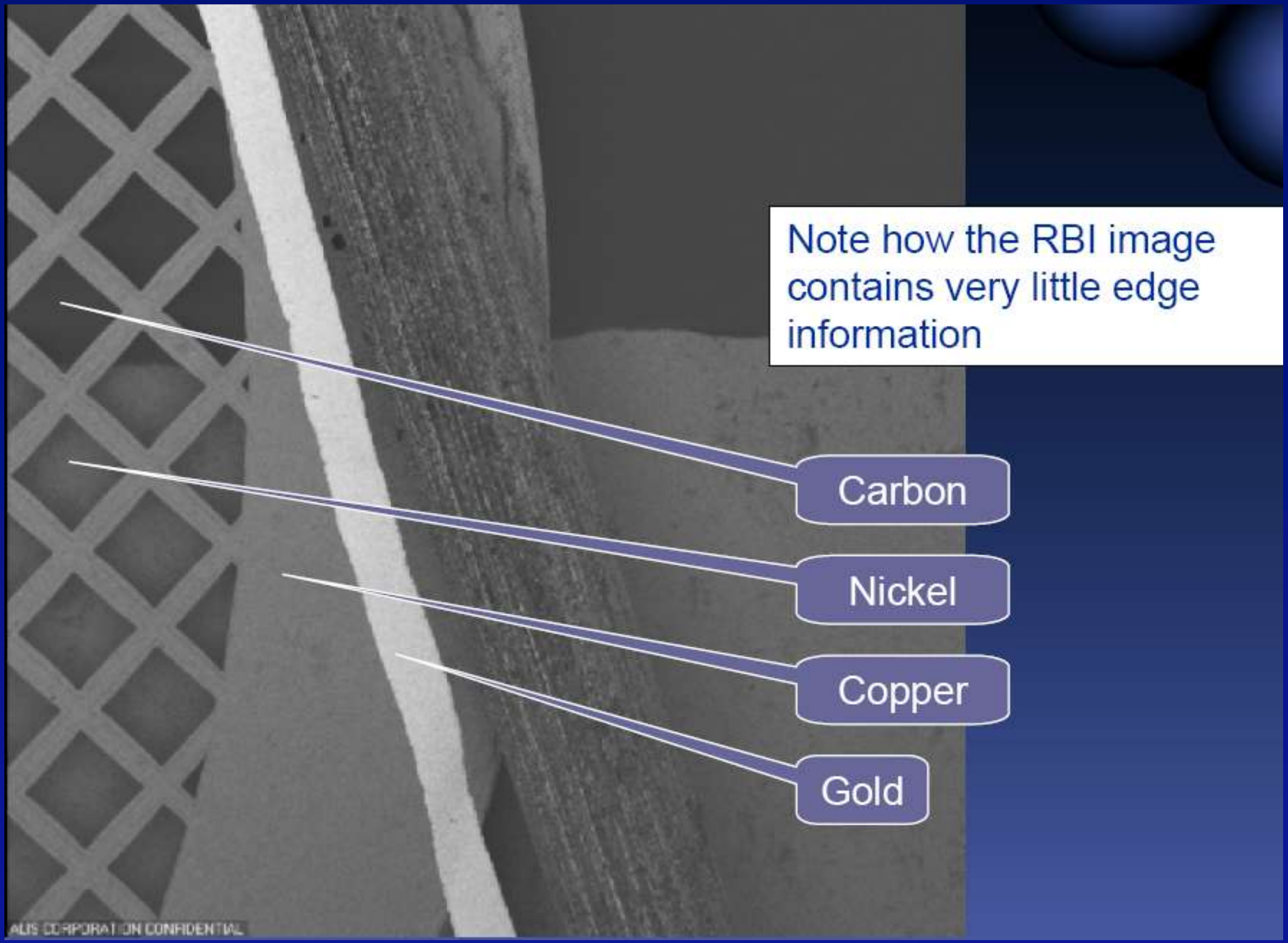
Long depth of field (~ 5x better than SEM)



He ion induced secondary electron images

Images courtesy Carl Zeiss Nano Technology Systems Division

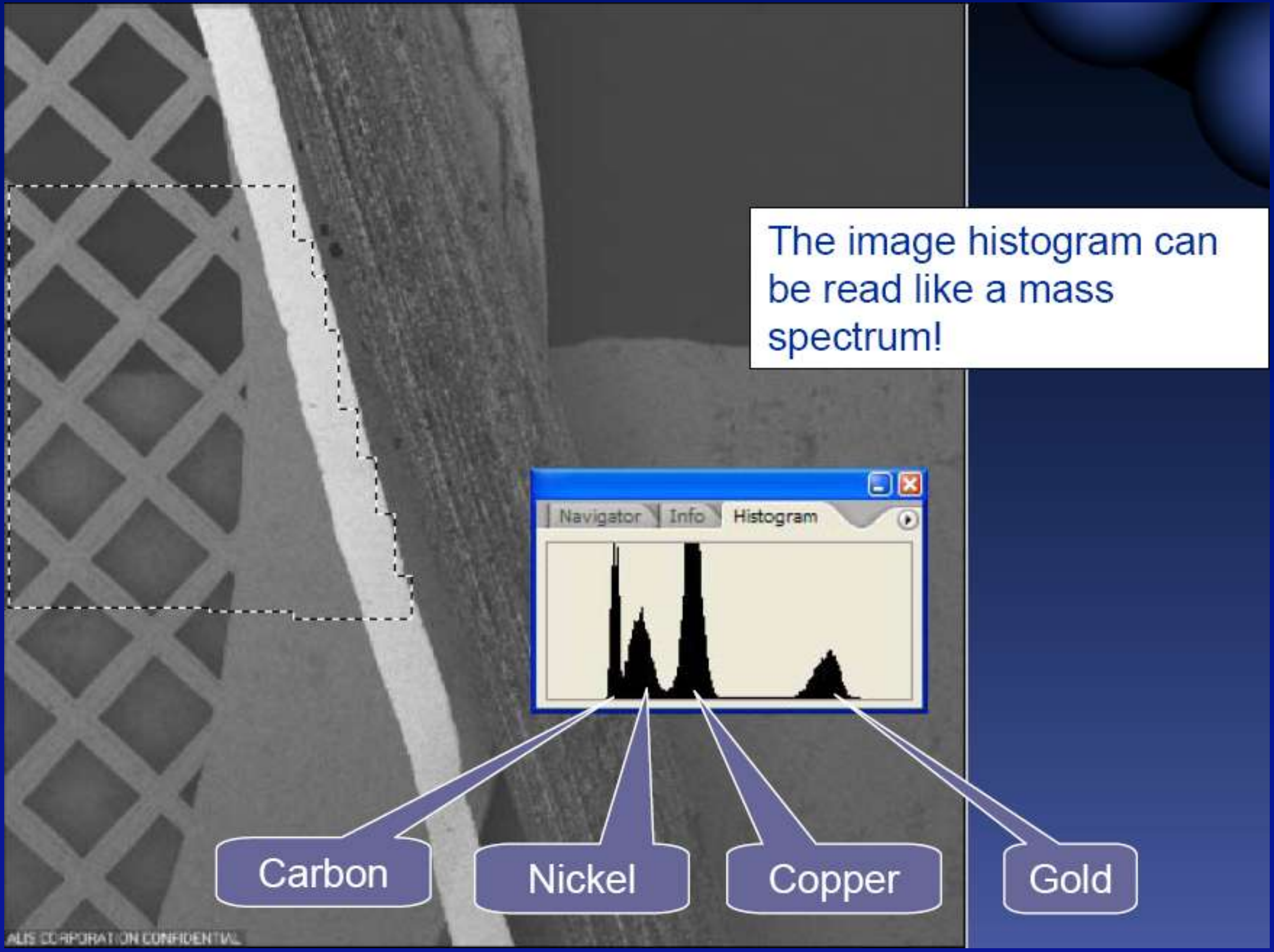
He Secondary Ion Imaging



He ion induced secondary ion image

Image courtesy Carl Zeiss Nano Technology Systems Division

He Secondary Ion Imaging

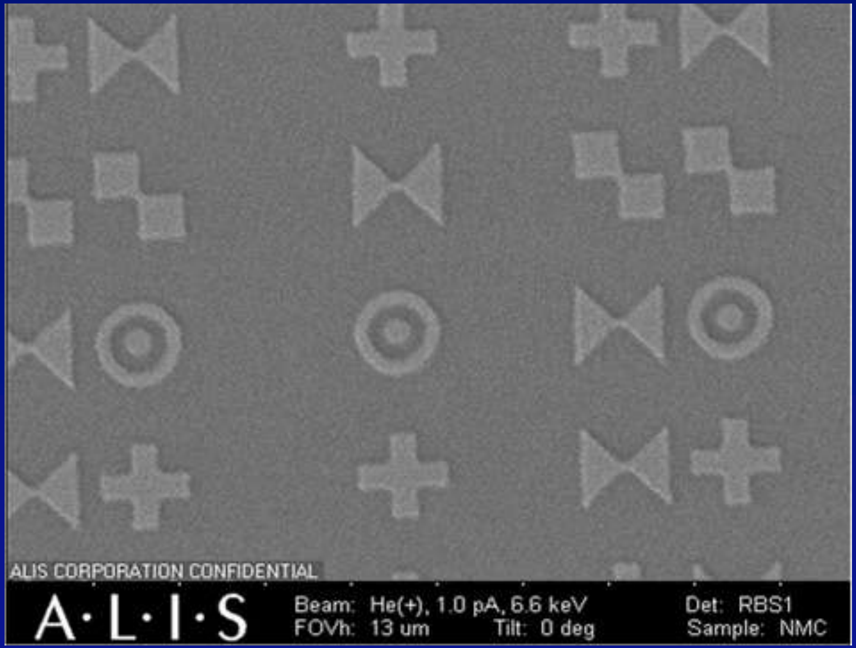


He ion induced secondary ion image

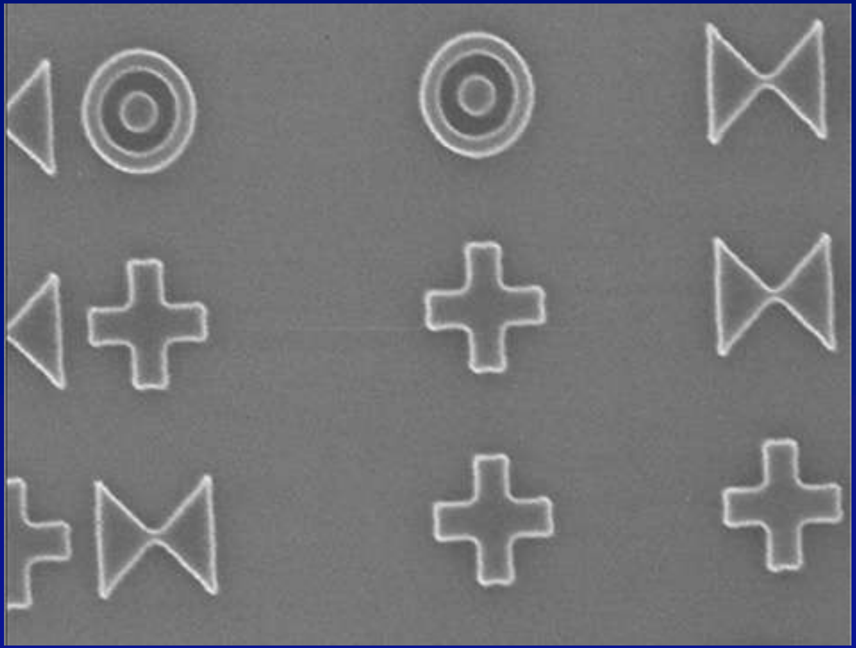
Image courtesy Carl Zeiss Nano Technology Systems Division

He Secondary Ion Imaging

Negligible edge effects compared to SEM



He ion induced secondary ion image



Electron microscope secondary electron image

Images courtesy Carl Zeiss Nano Technology Systems Division

He Ion Microscopy Summary

Small spot size ~ 0.25 nm
Small sample interaction volume
Image information:
 - Topographic information
 - Material information
 - Voltage contrast information
 - Crystallographic information
Long depth of field
Minimal charging artifacts
Transmission ion imaging

Data courtesy Carl Zeiss Nano Technology Systems Division